# Space-based CR experiments: Results and perspectives

SciNeGHE 2016

**Bruna Bertucci**

**University & INFN Perugia**

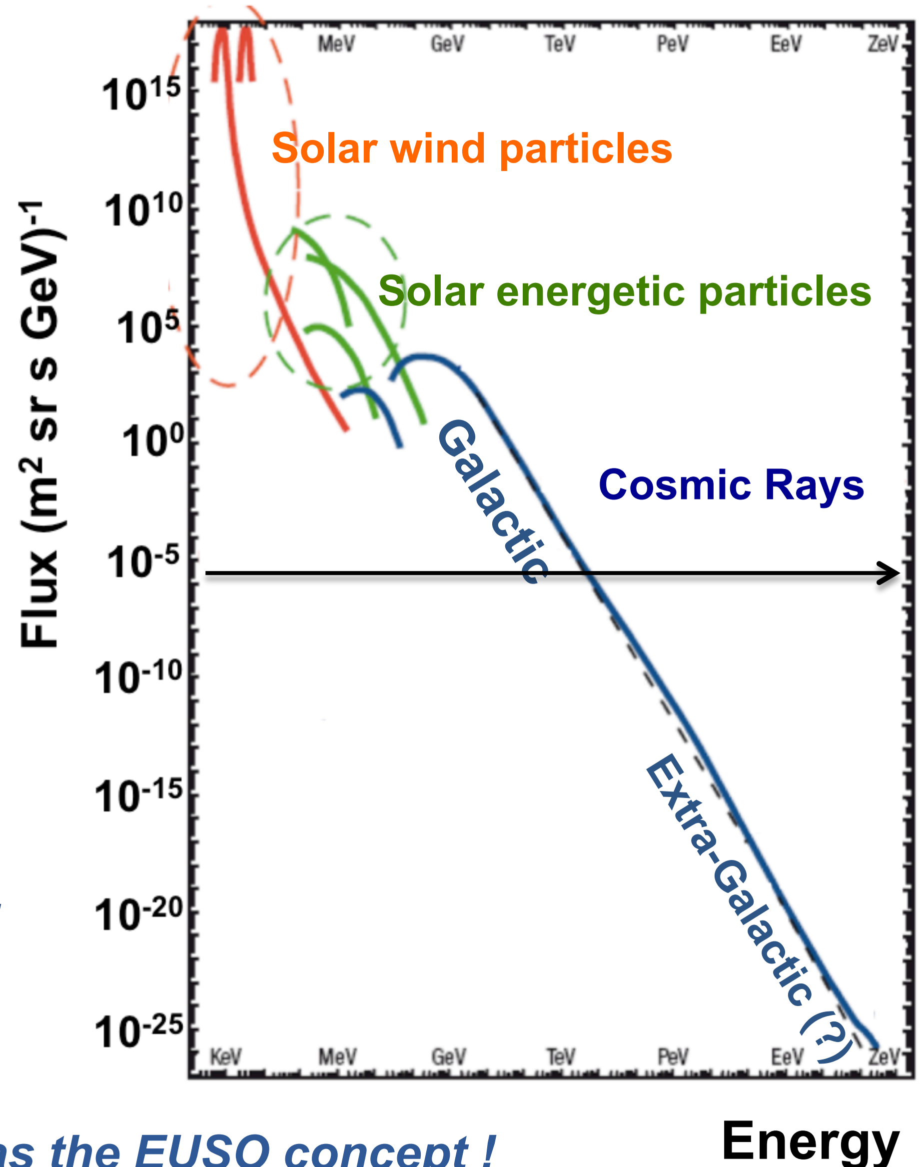
# CR spectrum : the overall picture

**Space**
**=**
**Direct CR measurements***

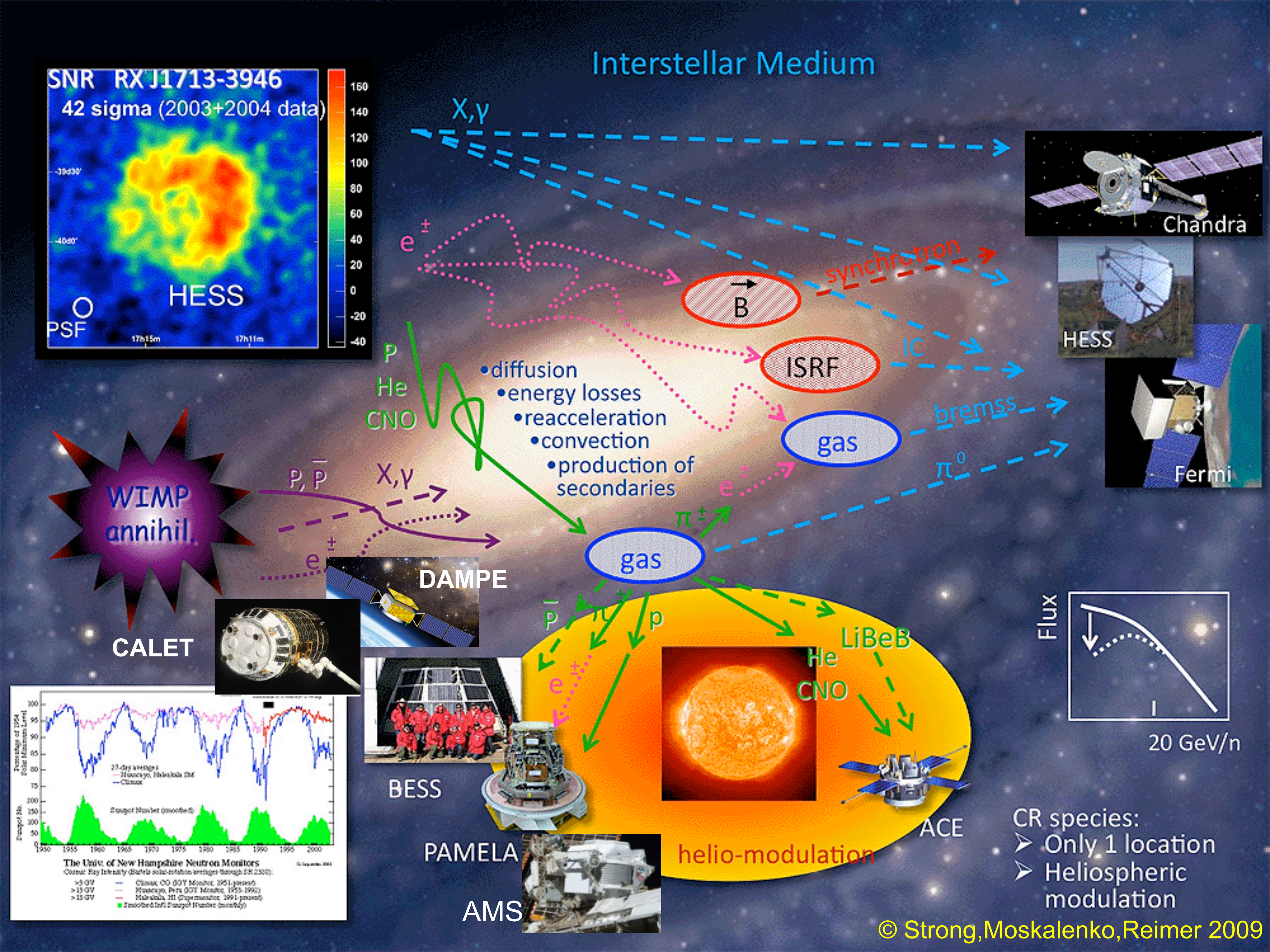
**Key points:**

- HEP techniques
- Particle Identification
- Good calibration of energy scale
- Mass/size constraints limits

*The everlasting challenge:*
*collection factor ($m^2$sr yr) increase...*

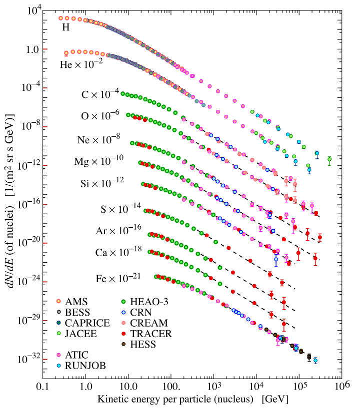


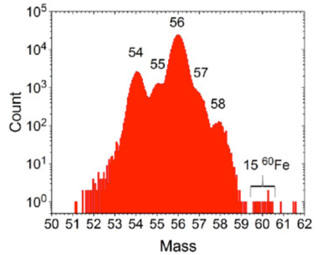

*** with some noticeable exceptions : as the EUSO concept !***


Interstellar Medium
SNR RX J1713-3946
42 sigma (2003+2004 data)
HESS
PSF
X,γ
e±
B
synchrotron
ISRF
IC
gas
bremss
π0
P
He
CNO
•diffusion
•energy losses
•reacceleration
•convection
•production of secondaries
WIMP annihil.
P, P̄
X,γ
e±
π±
gas
P̄
π±
p
e±
LiBeB
He
CNO
Chandra
HESS
Fermi
DAMPE
CALET
BESS
PAMELA
AMS
ACE
helio-modulation
Flux
20 GeV/n
CR species:
Only 1 location
Heliospheric modulation
The Univ. of New Hampshire Neutron Monitors
© Strong,Moskalenko,Reimer 2009

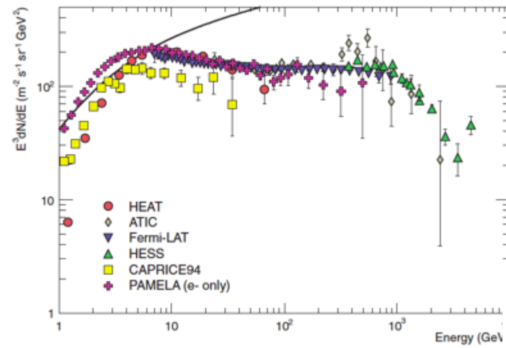
# Space Based measurements

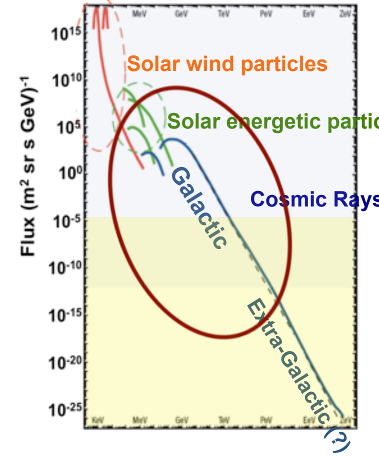
## Chemical composition




## The electron component



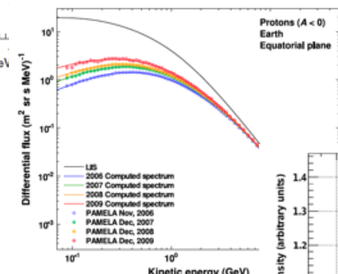

## Earth & Sun

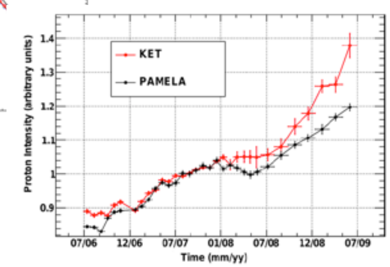
Sources

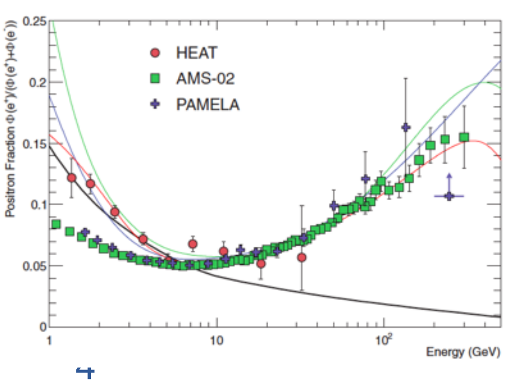
Propagation

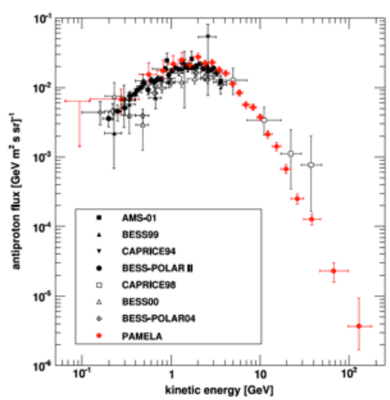
ISM

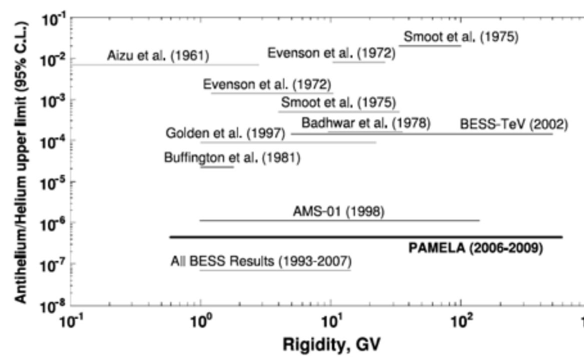
New Physics?




## Anti-matter

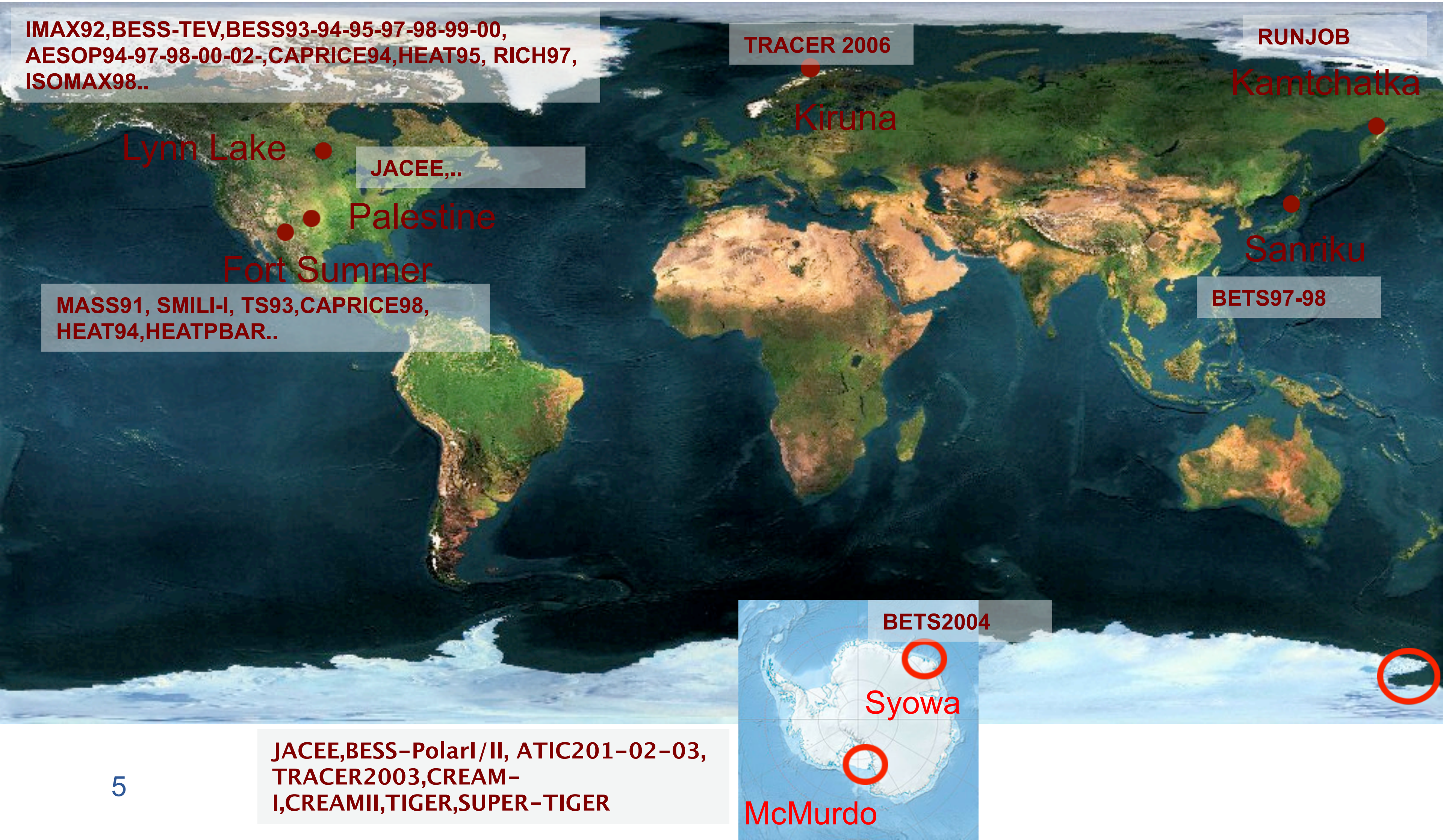
# Stratospheric Balloons: from few hrs to months

**Magnetic Spectrometers**

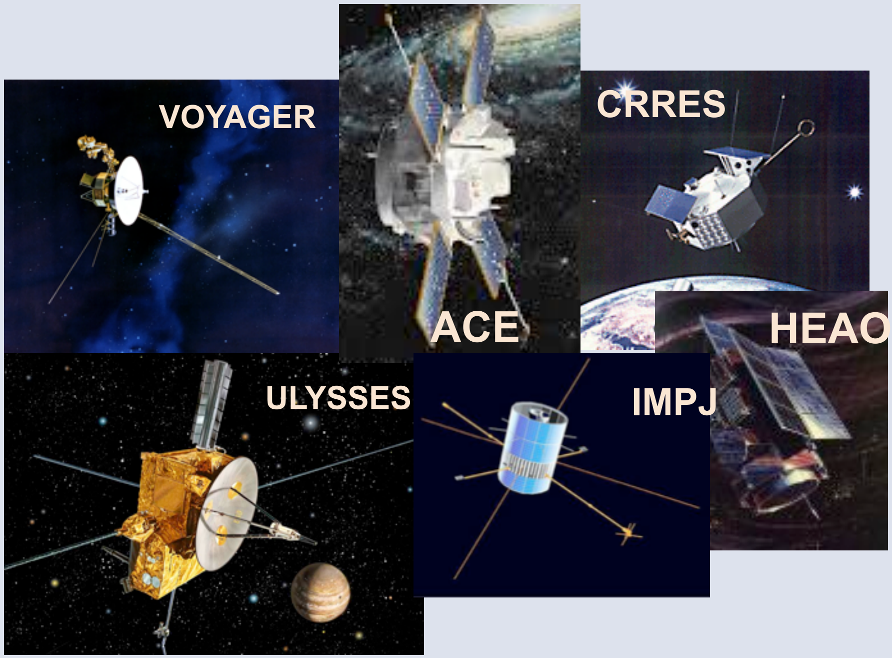
…
BESS/POLAR/TEV (9 Flights)
WIZARD (6,Flights)
HEAT/PBAR (4,Flights)

**Calorimetry, TRD +..**

RUNJOB (62 day, 10 Flights)
TRACER (18 days, 3 Flights)
CREAM (161 days,6 Flights)
ATIC (53 days, 3 Flights)
TIGER/S-TIGER (2/55 days)



# Space:



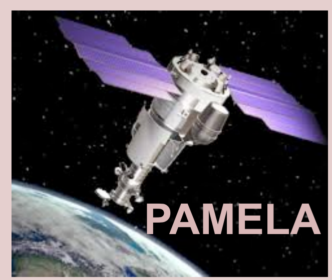

**Long missions (years)**
**Small payloads**
**Low energies..**

IMP series < GeV/n
ACE-CRIS/SIS Ekin < GeV/n
VOYAGER-HET/CRS < 100 MeV/n
ULYSSES-HET (nuclei) < 100 MeV/n
ULYSSES-KET (electrons) < 10 GeV
CRRES/ONR < (nuclei) 600 MeV/n
*HEAO3-C2 (nuclei) < 40 GeV/n*

## Short missions (days)/ Larger payloads

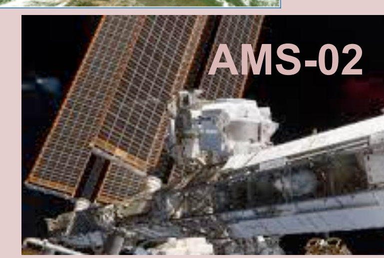
**CRN on Challenger**
(3.5 days 1985)


**AMS-01 on Discovery**
(8 days, 1998)





**Long missions**
**Large payloads**





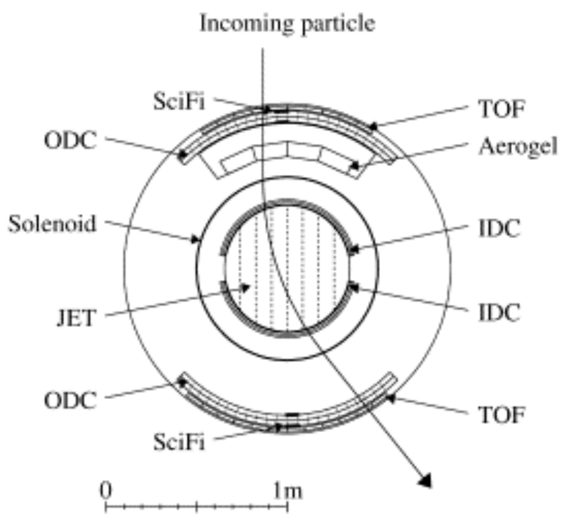
# Anti-matter?

Primordial anti-matter
DM indirect searches

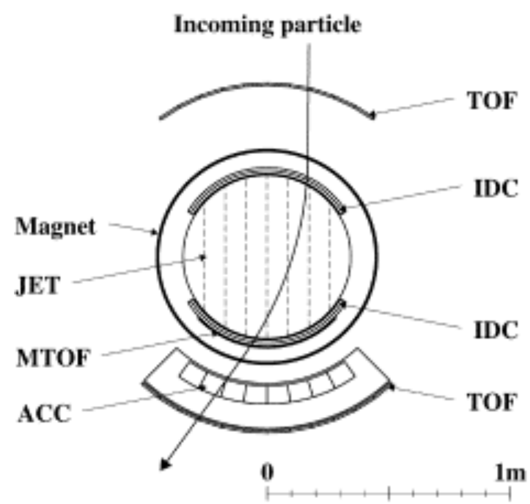
Z>1
positrons (and electrons)
anti-protons

# Balloon borne Experiment with Superconducting Spectrometer BESS: 9 flights between 1993 and 2004

- large solenoidal thin-wall superconducting magnet: 0.3 $m^2$sr, 0.8 T
- a time-of-flight system of scintillation counter hodoscopes
- inner drift chambers (IDC)
- a jet-type drift particle-tracking chamber
- outer drift chambers / aerogel Cherenkov counter depending on the configuration

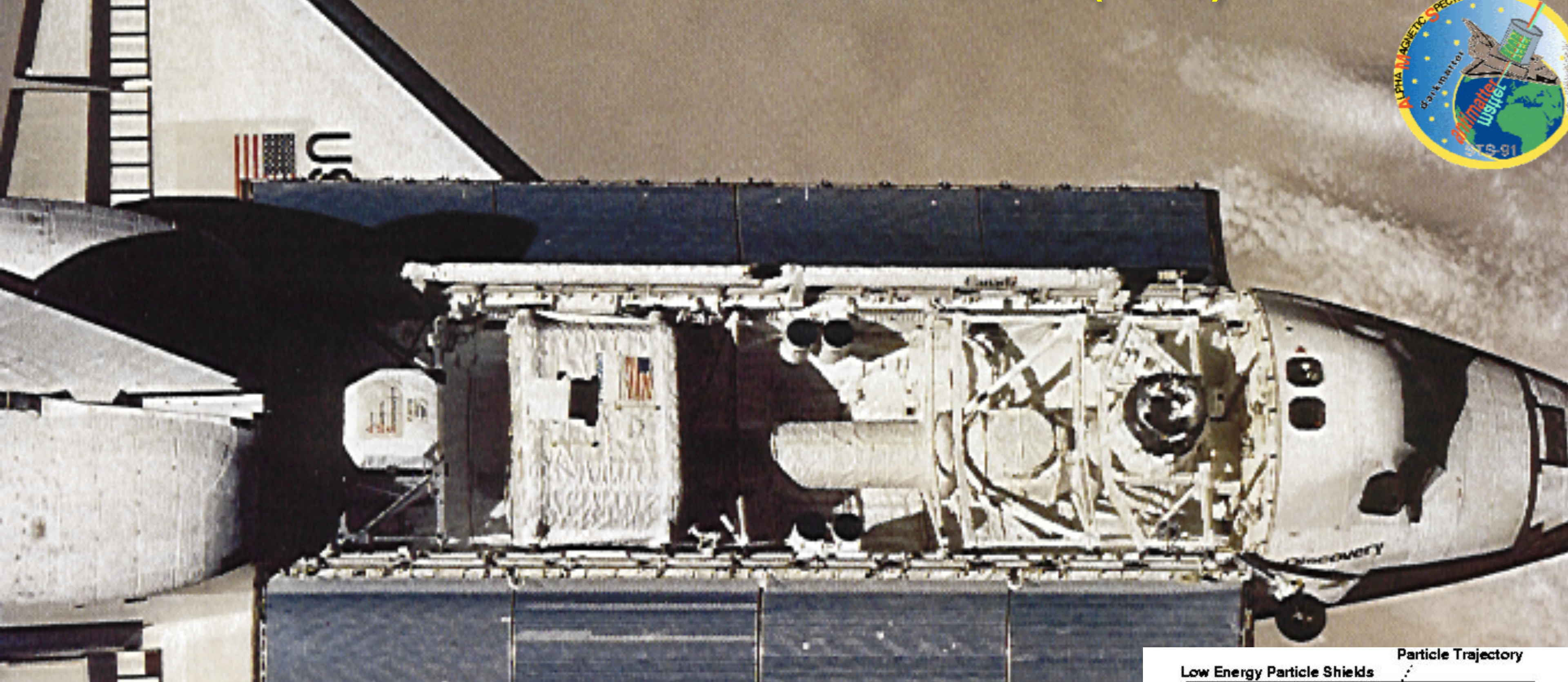


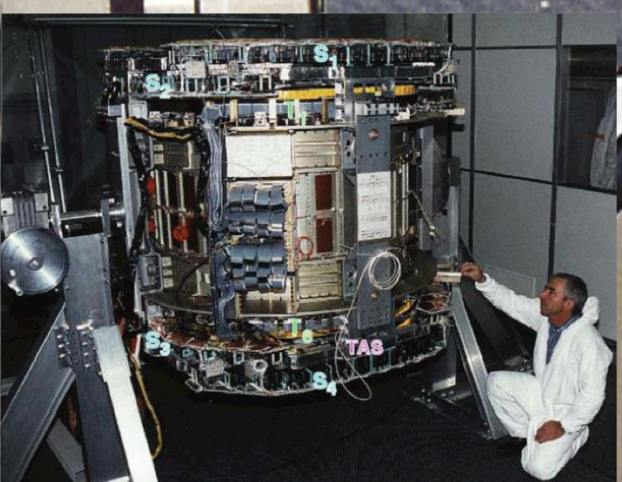

BESS-TeV
MDR 1.4 TV

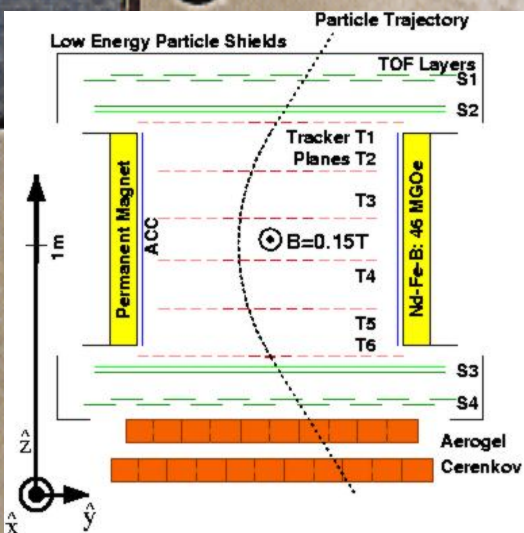



BESS-Polar
MDR 240 GV

# Alpha Magnetic Spectrometer on STS-91
# AMS-01 (1998)



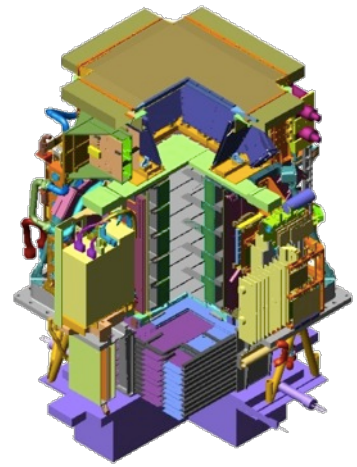


# **Pa**yload for **M**atter/Antimatter **E**xploration and **L**ight nuclei **A**strophysics - **PAMELA**

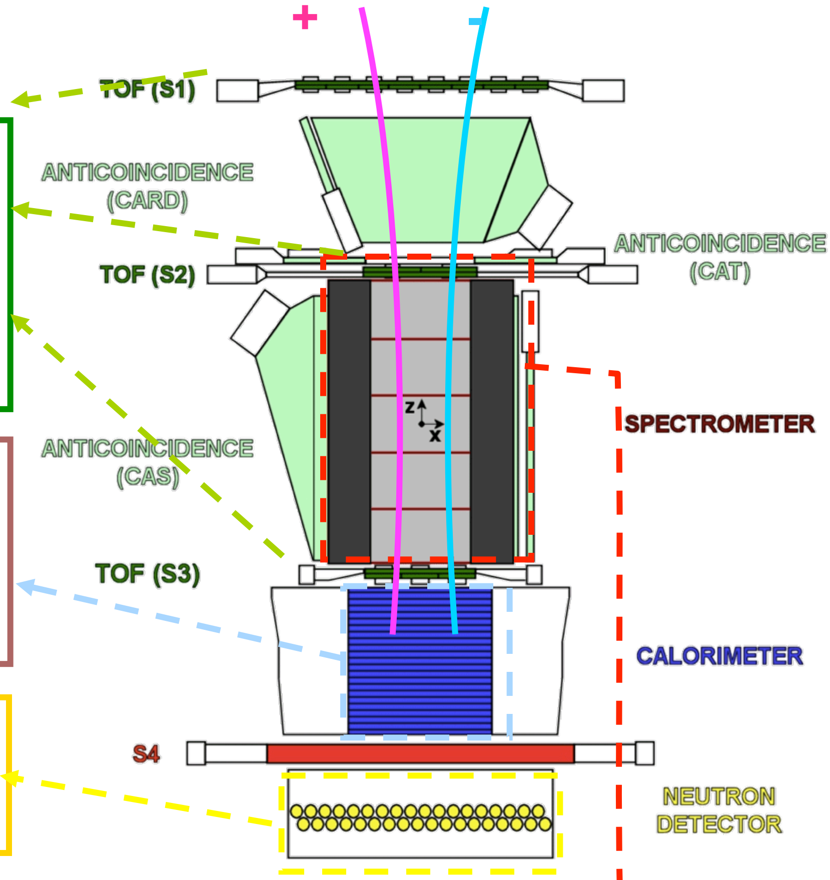
→ **Launched on 15th June 2006**
→ **PAMELA in continuous data-taking mode for 10 years**


Launch from Baykonur



- PAMELA on board of Russian satellite **Resurs DK1**
- Orbital parameters:
  - inclination ~$70^o$ (⇒ low energy)
  - altitude ~ 360-600 km (elliptical)
  - active life >3 years (⇒ high statistics)

# The detector




**Time-Of-Flight**
**plastic scintillators + PMT:**
- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX.

**Electromagnetic calorimeter**
**W/Si sampling (16.3 X0, 0.6 λI)**
- Discrimination e+ / p, anti-p / $e^-$ (shower topology)
- Direct E measurement for $e^-$

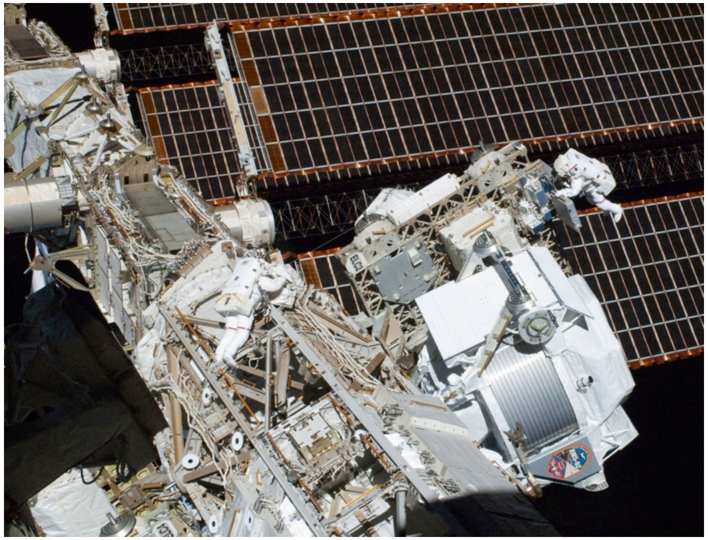
**Neutron detector**
**36 $He^3$ counters :**
- High-energy e/h discrimination

**Spectrometer**
**microstrip silicon tracking system + permanent magnet**
It provides:
- *Magnetic rigidity* → R = pc/Ze MDR≈1(0.25) TV
- *Charge sign*
- *Charge value from dE/dx*

**GF: 21.5 $cm^2$ sr**
**Mass: 470 kg**
**Size: 130x70x70 $cm^3$**
**Power Budget: 360W**

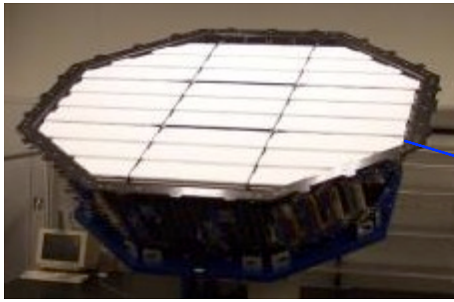
# Alpha Magnetic Spectrometer on the ISS: AMS-02

→ Launched on May 16, 2011
→ Installed on ISS May 19, 2011
→ AMS-02 foreseen to operate for the entire ISS lifetime



# AMS-02: the detector

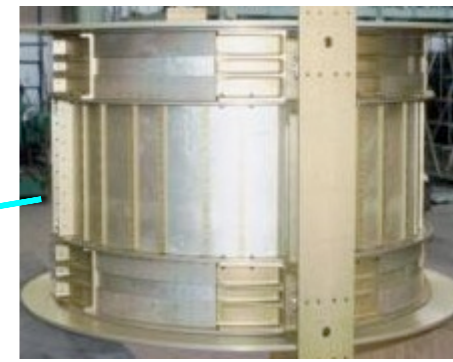
**Transition Radiation Detector**
**Identify electrons**



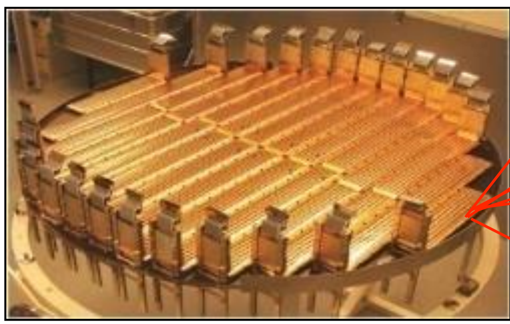
**Particles are defined by their charge (Z) and energy (E) or momentum (P)**

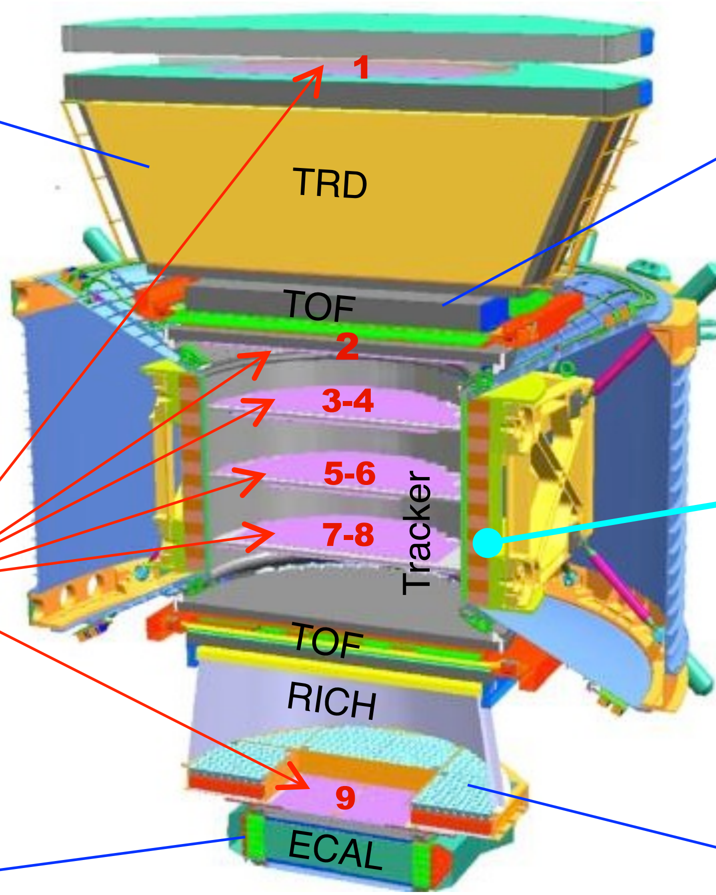
**Time of Flight**
**Z, E**

**Magnet**
**±Z**



**Silicon Tracker**
**Z, P**





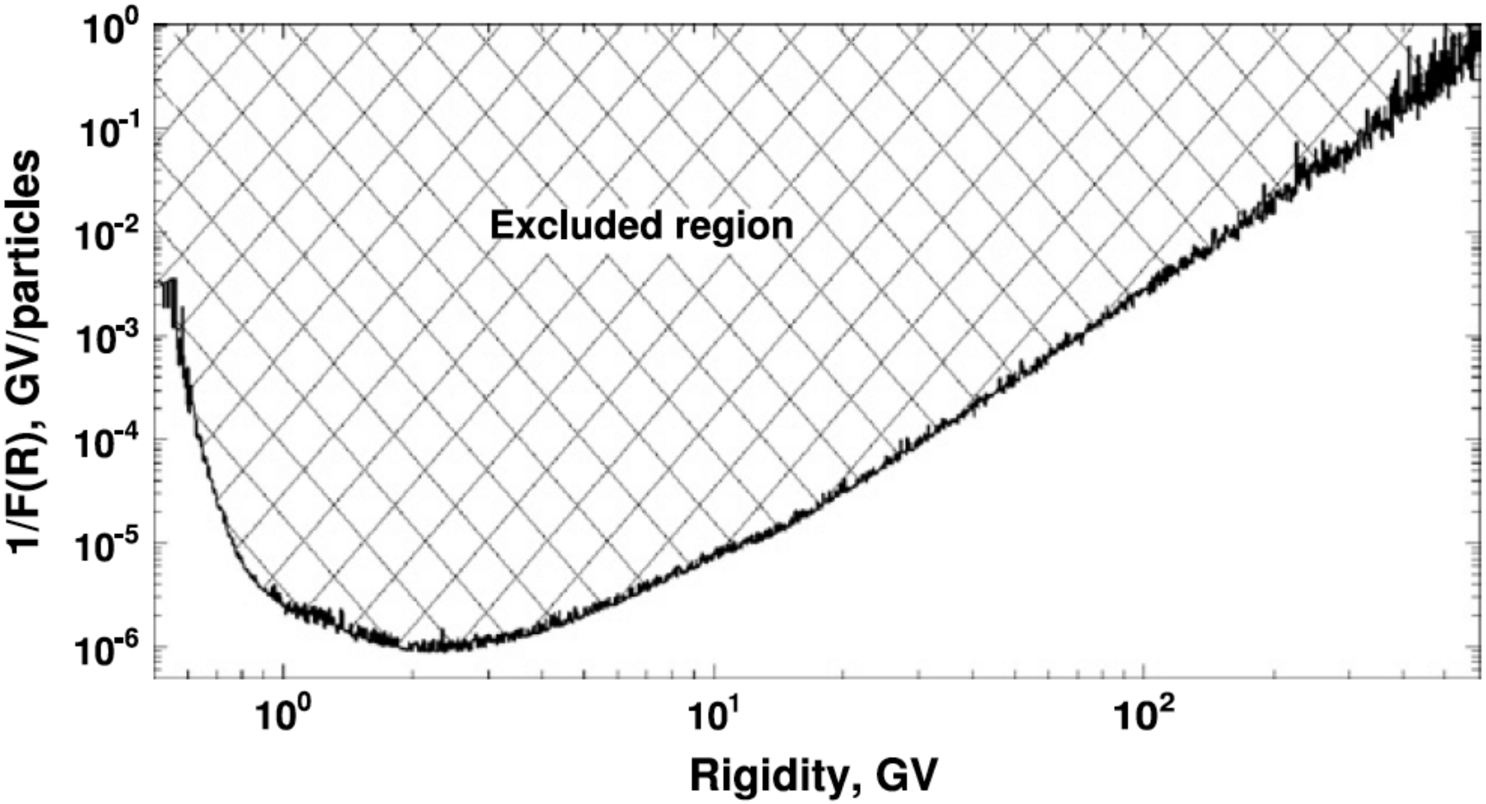

**Ring Imaging Cherenkov**
**Z, E**

**Electromagnetic Calorimeter**
**E of electrons**

***The Charge and Energy (momentum) are measured independently by many detectors***

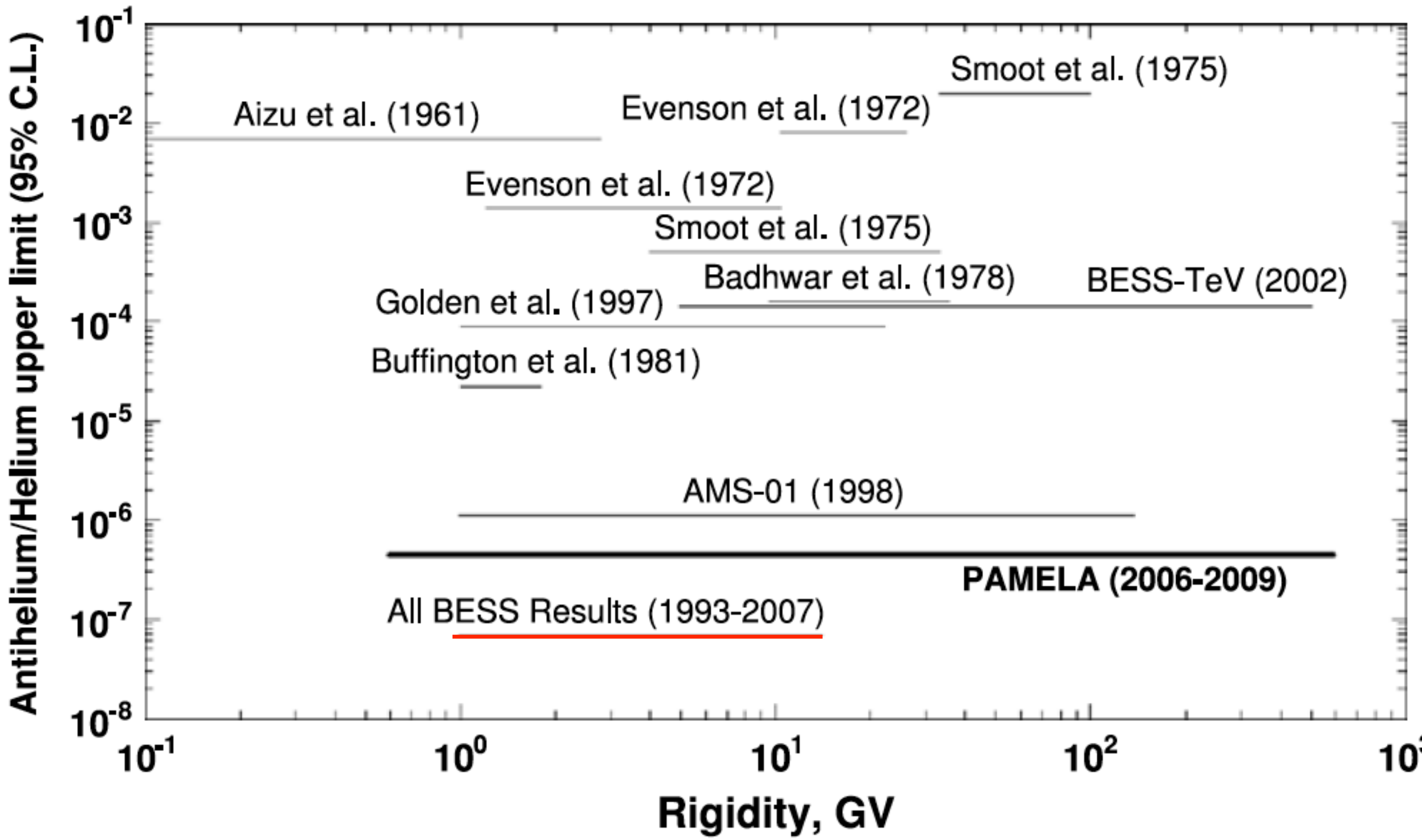
# Anti-He/He

differential upper limit with 6.3 M He events collected in PAMELA




$$\frac{N_{\overline{He}}(R_i;R_f)}{N_{He}(R_i;R_f)} < \frac{3}{\int_{R_i}^{R_f} F(R)dR} = \frac{3}{\int_{R_i}^{R_f} \frac{dN'_{He}(R)}{dR} dR} \cdot \frac{\epsilon_{He}(R_i;R_f)}{\epsilon_{\overline{He}}(R_i;R_f)},$$

# Anti-He/He




**Waiting for AMS-02 ......**

# Anti-matter?

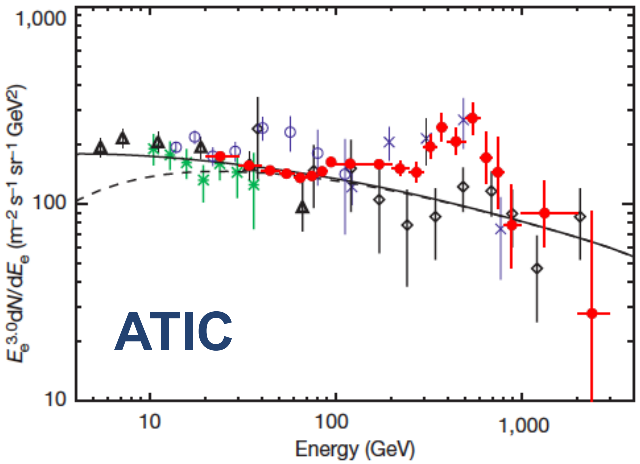
Primordial anti-matter
DM indirect searches

Z>1 Anti-matter
**positrons (and electrons)**
anti-protons

# 2008-2009: the $e^+/e^-$ puzzle

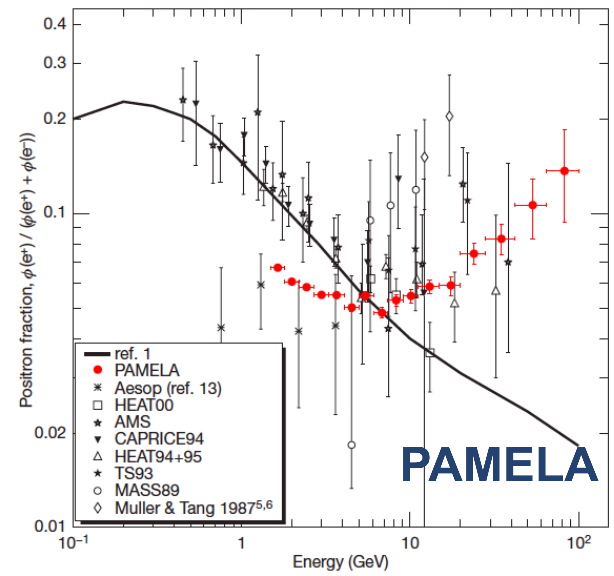
**An excess of cosmic ray electrons at energies of 300–800 GeV**

Vol 456 | 20 November 2008 | **doi:10.1038/nature07477**



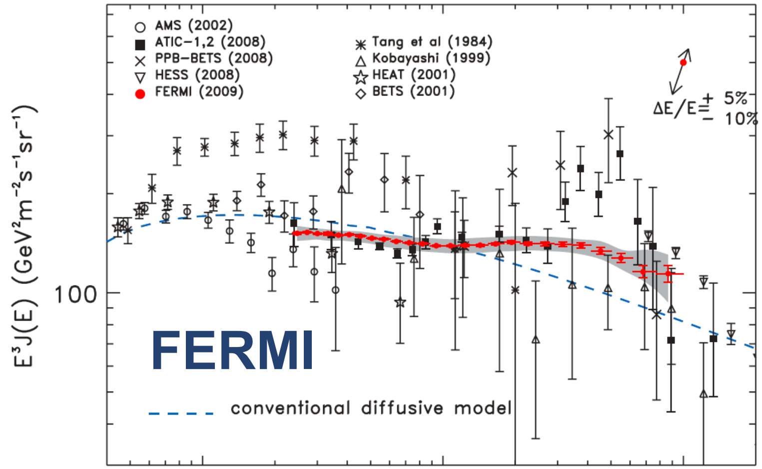

**An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV**

Vol 458 | 2 April 2009 | **doi:10.1038/nature07942**




**Measurement of the Cosmic Ray $e^+ + e^-$ Spectrum from 20 GeV to 1 TeV with the Fermi Large Area Telescope**

PRL **102,** 181101 (2009)

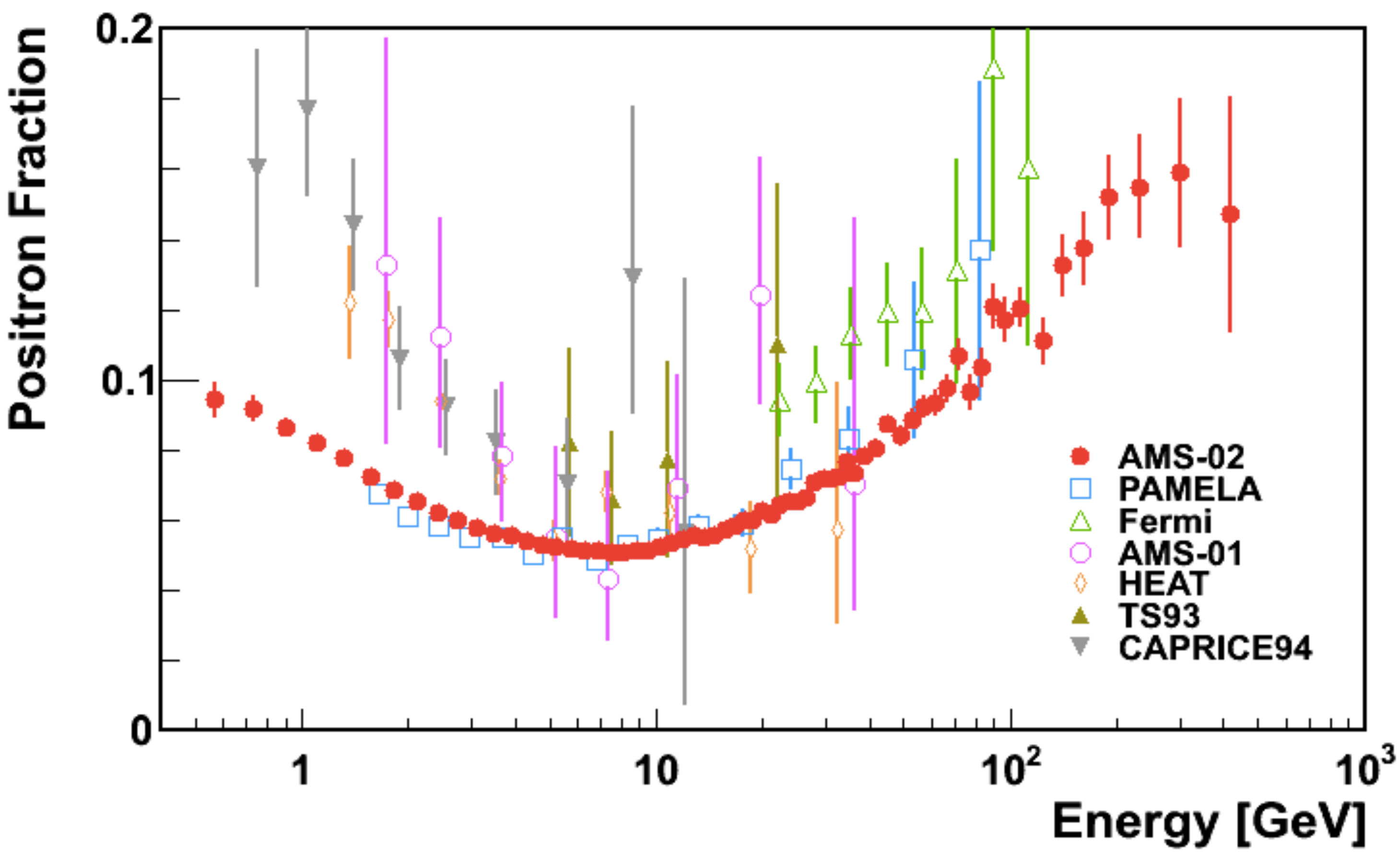


# The actual status (not the end of the story)

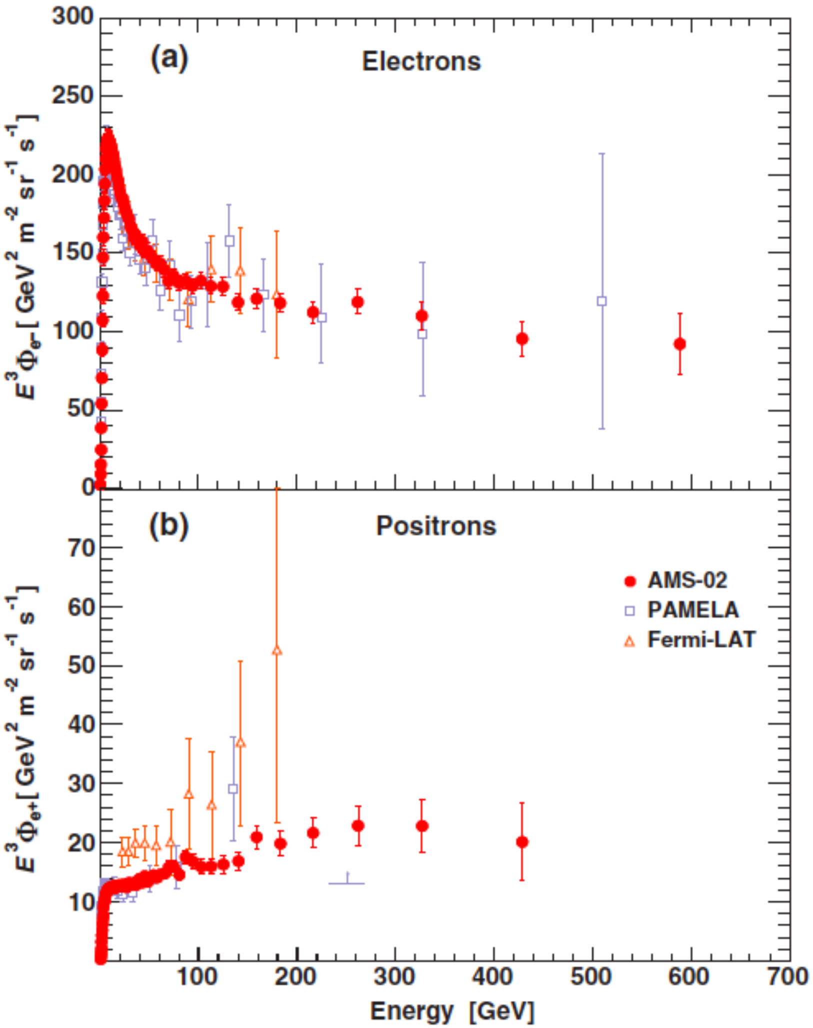
PRL **113,** 121101 (2014) PHYSICAL REVIEW LETTERS week ending 19 SEPTEMBER 2014

**High Statistics Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5–500 GeV with the Alpha Magnetic Spectrometer on the International Space Station**

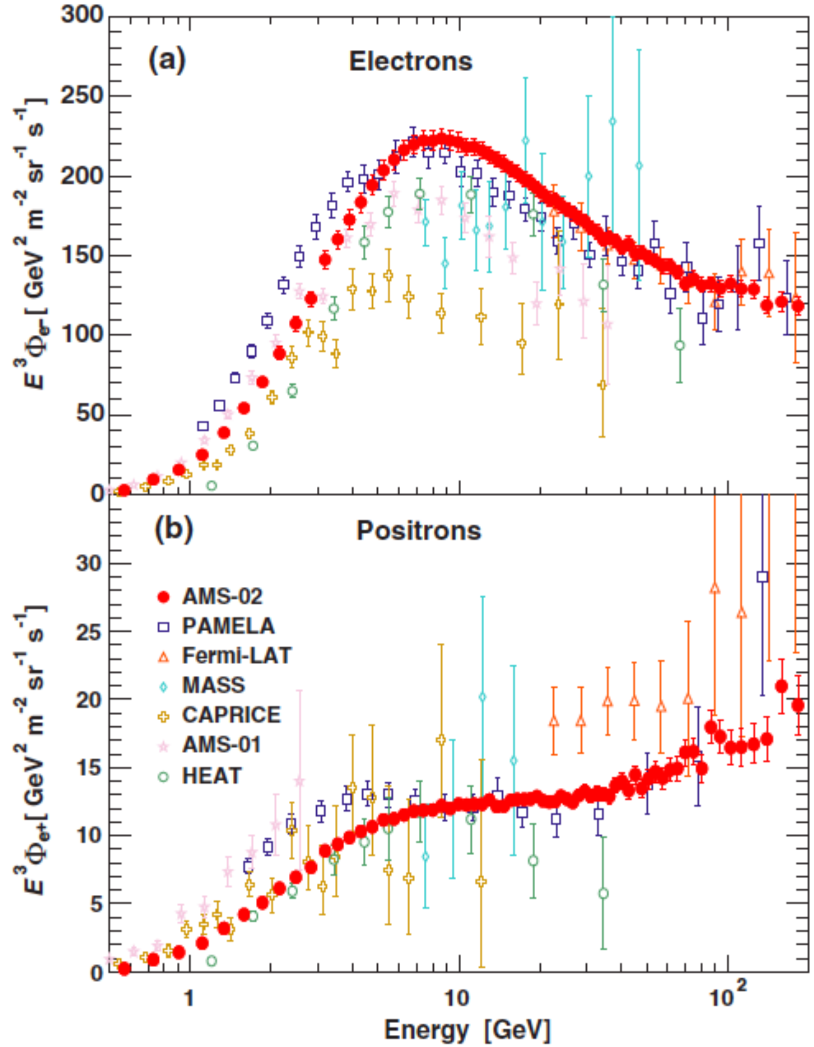
10.9 million e+ and e- events



# e+/e- fluxes

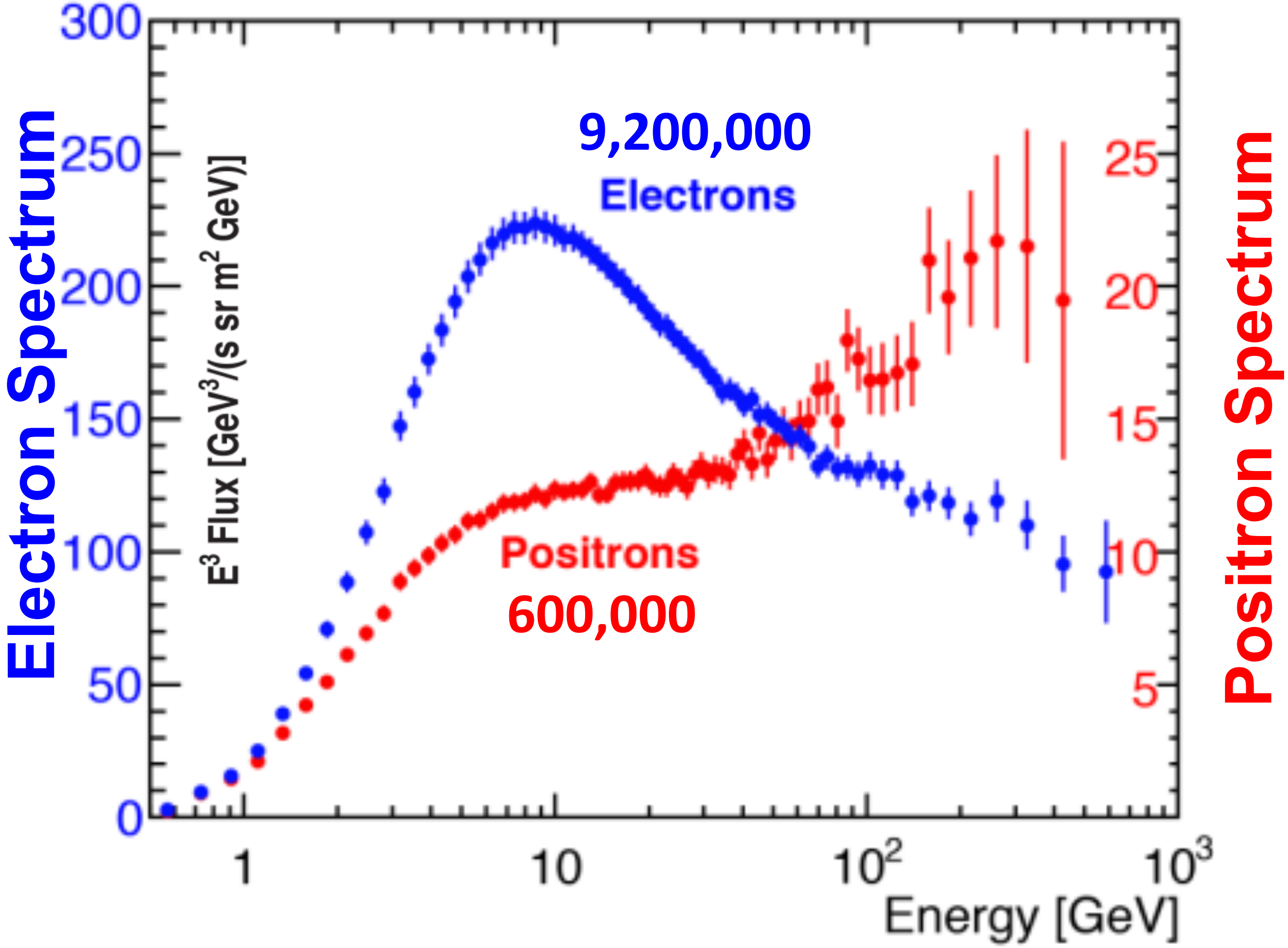


(a)
Electrons
(b)
Positrons
AMS-02
PAMELA
Fermi-LAT
$E^3\Phi_{e-}$[ GeV$^2$ m$^{-2}$ sr$^{-1}$ s$^{-1}$]
$E^3\Phi_{e+}$[ GeV$^2$ m$^{-2}$ sr$^{-1}$ s$^{-1}$]
Energy [GeV]

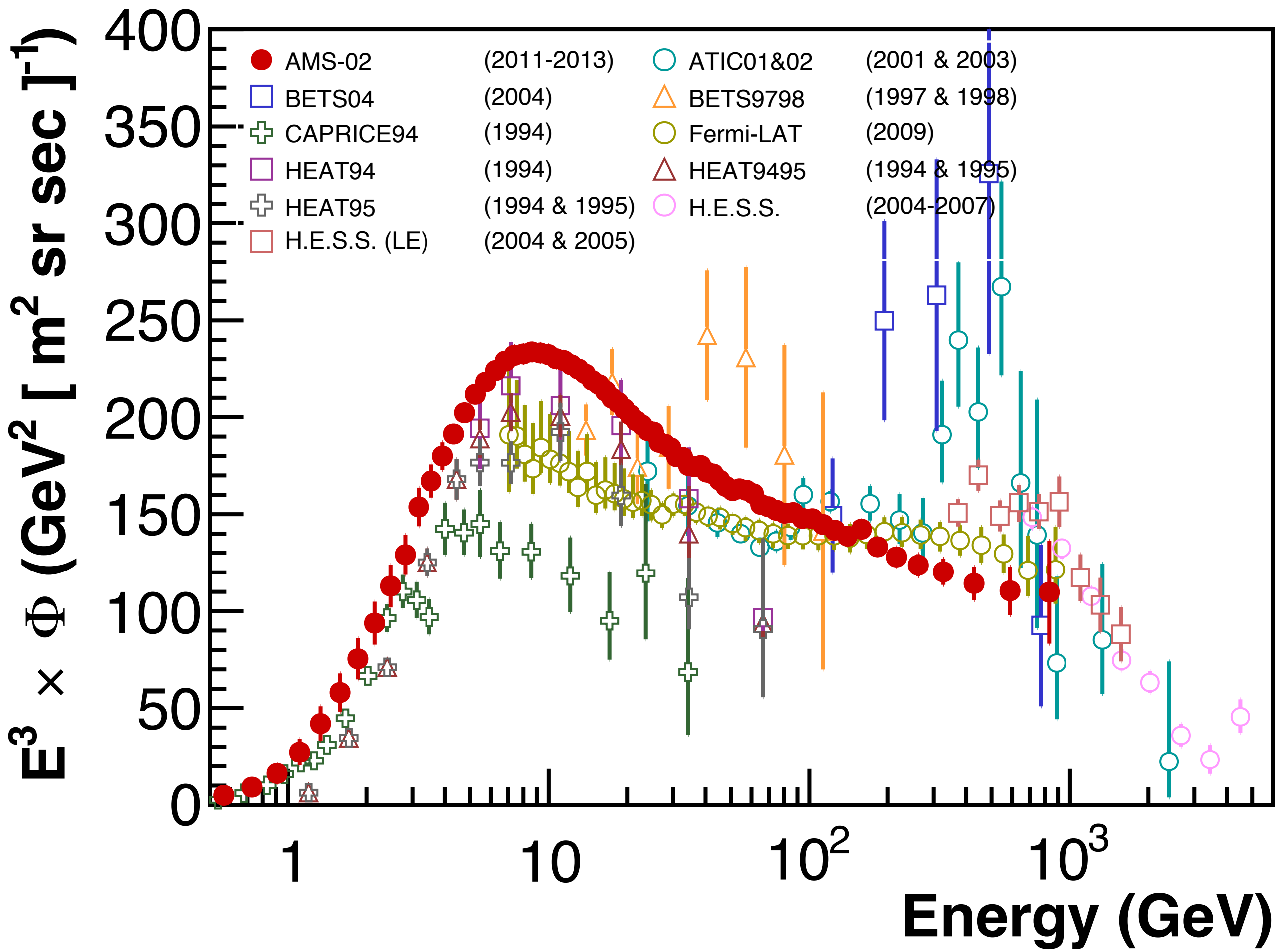
(a)
Electrons
(b)
Positrons
AMS-02
PAMELA
Fermi-LAT
MASS
CAPRICE
AMS-01
HEAT
$E^3\Phi_{e-}$[ GeV$^2$ m$^{-2}$ sr$^{-1}$ s$^{-1}$]
$E^3\Phi_{e+}$[ GeV$^2$ m$^{-2}$ sr$^{-1}$ s$^{-1}$]
Energy [GeV]

# e+/e- fluxes



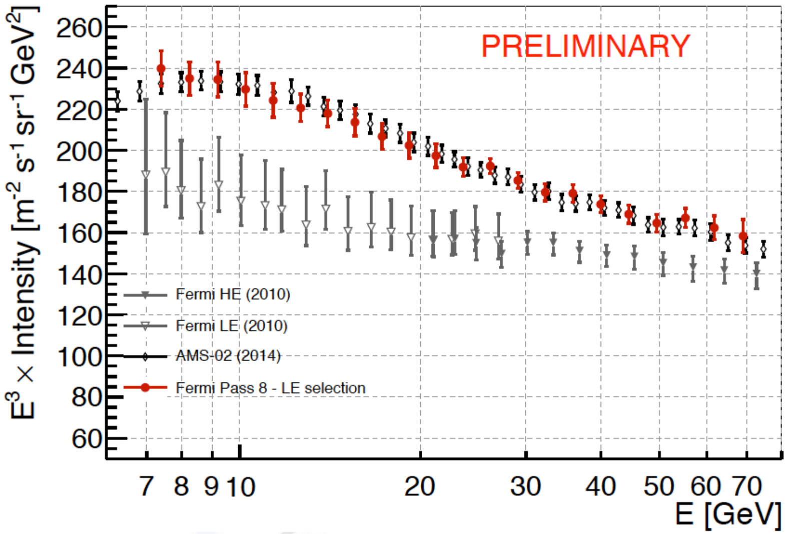
Electron Spectrum
Positron Spectrum
9,200,000
Electrons
Positrons
600,000
E^3 Flux [GeV^3/(s sr m^2 GeV)]
Energy [GeV]
300
250
200
150
100
50
0
25
20
15
10
5
1
10
10^2
10^3

# e⁺+e⁻ fluxes



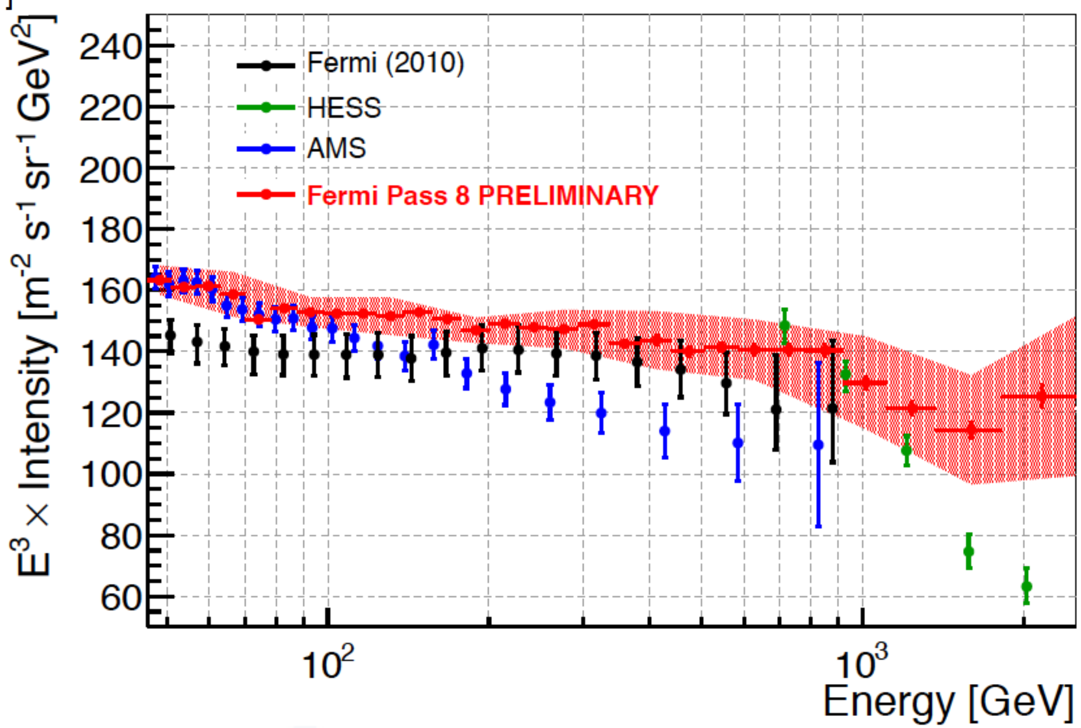
AMS-02 (2011-2013)
BETS04 (2004)
CAPRICE94 (1994)
HEAT94 (1994)
HEAT95 (1994 & 1995)
H.E.S.S. (LE) (2004 & 2005)
ATIC01&02 (2001 & 2003)
BETS9798 (1997 & 1998)
Fermi-LAT (2009)
HEAT9495 (1994 & 1995)
H.E.S.S. (2004-2007)
$E^3 \times \Phi$ (GeV$^2$ [ m$^2$ sr sec ]$^{-1}$)
0
50
100
150
200
250
300
350
400
1
10
$10^2$
$10^3$
Energy (GeV)

# e+e- fluxes @ SciNeGhe (see.18/10)




Waiting for new results from:

- + AMS
- + CALET
- + DAMPE



# Anti-matter?

Primordial anti-matter
DM indirect searches

Z>1 Anti-matter
positrons (and electrons)
**anti-protons**

# Anti-proton/proton

the early times (1984)

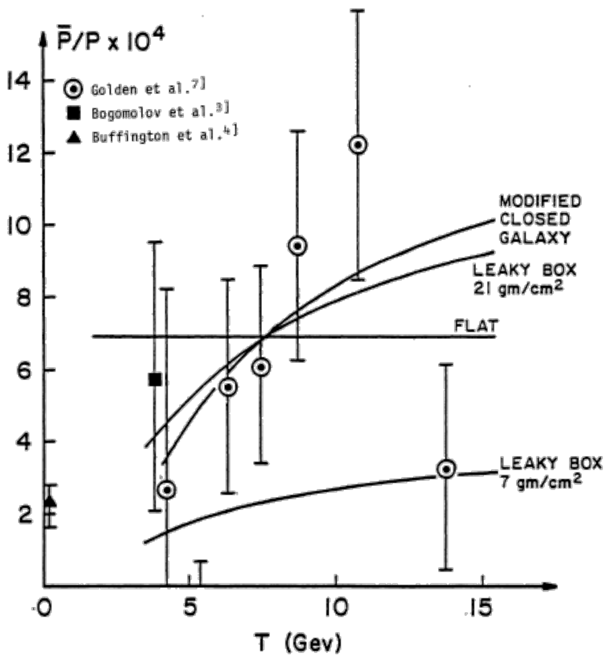
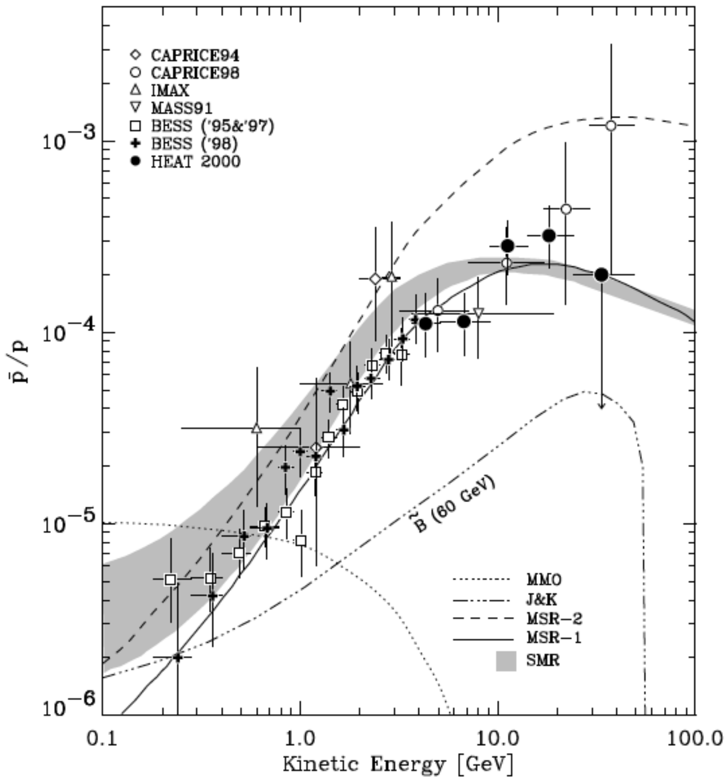



Figure 1. Antiproton Observations and Predictions

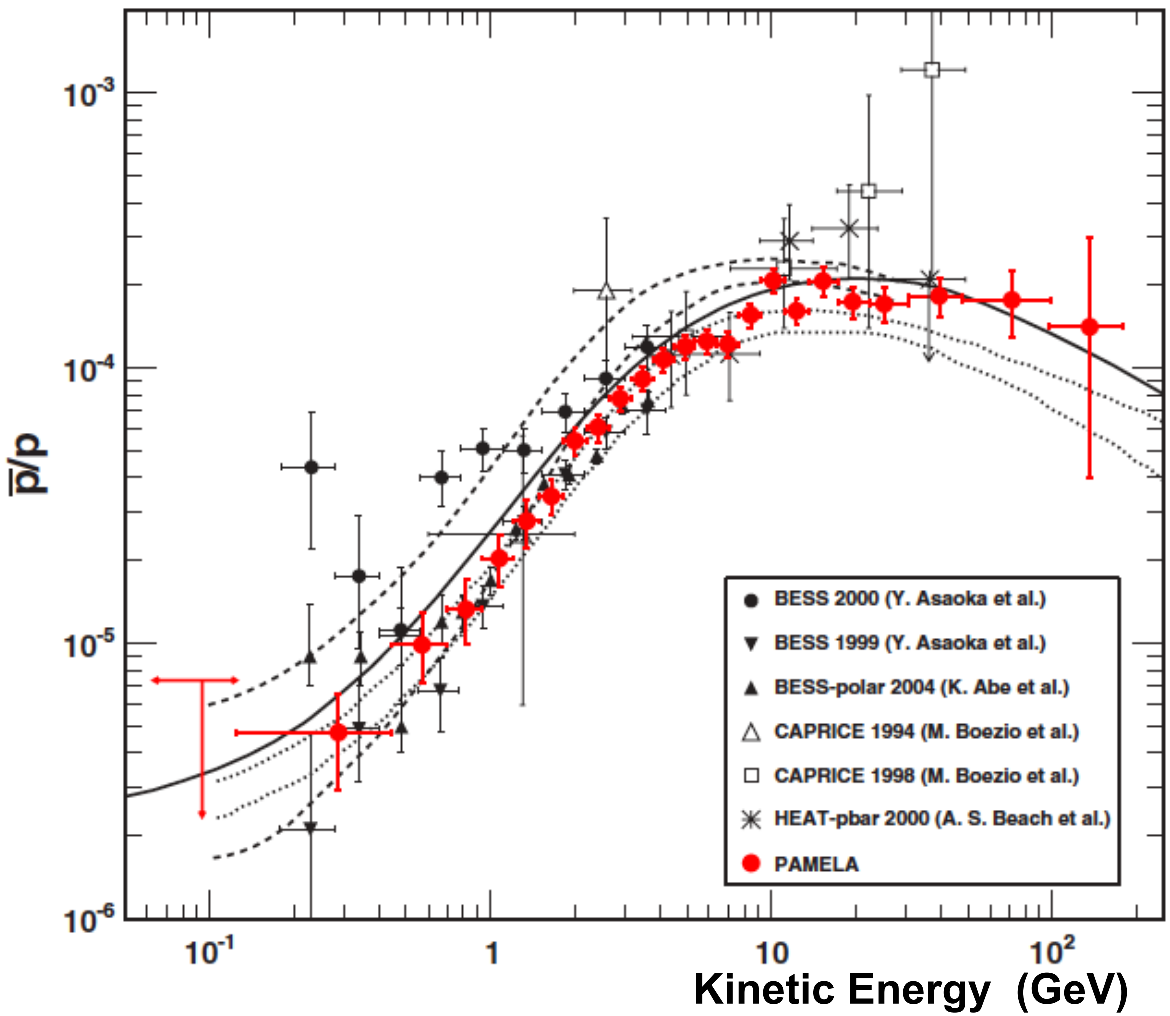
...around 2000




HEAT ≈ 70 events
CAPRICE ≈ 31 events

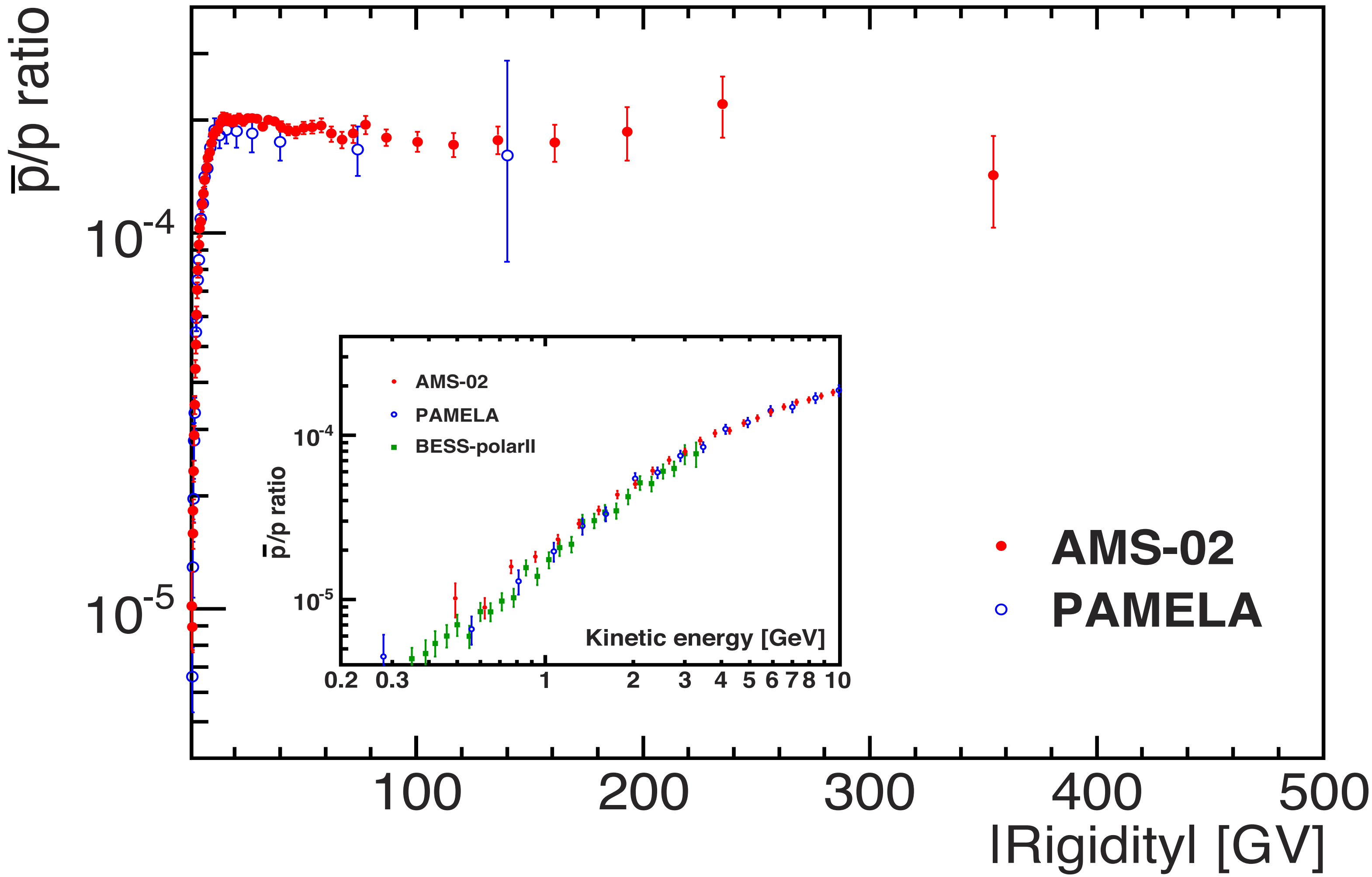
# Anti-proton/proton : 2010

BESS-POLAR (2004) ≈ 1520 event < 4.2 GeV
PAMELA (2006-2009) ≈ 1500 events



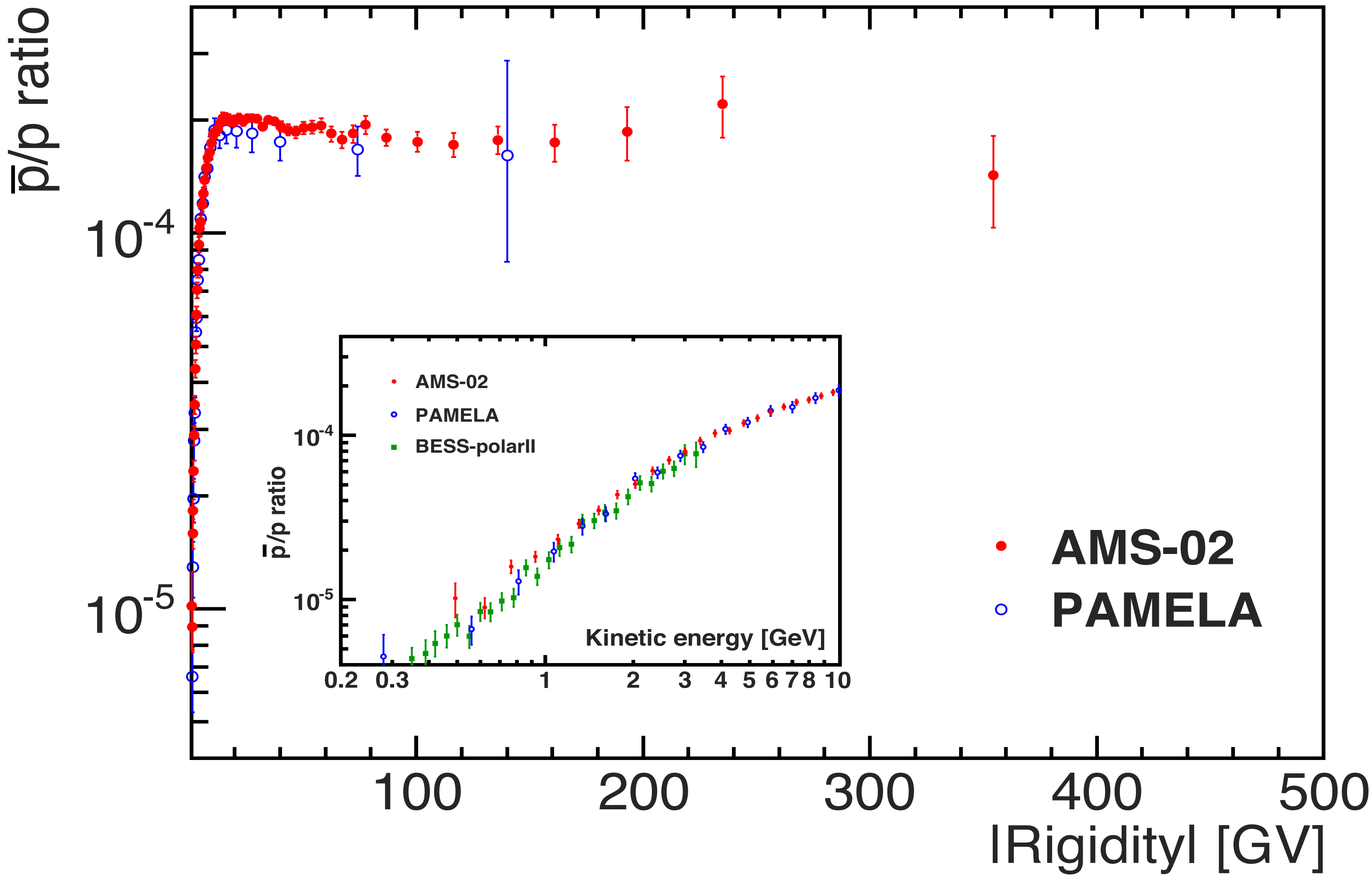
# Anti-protons/proton: 2016

PRL **117**, 091103 (2016)   ≈ 350,000 anti-protons



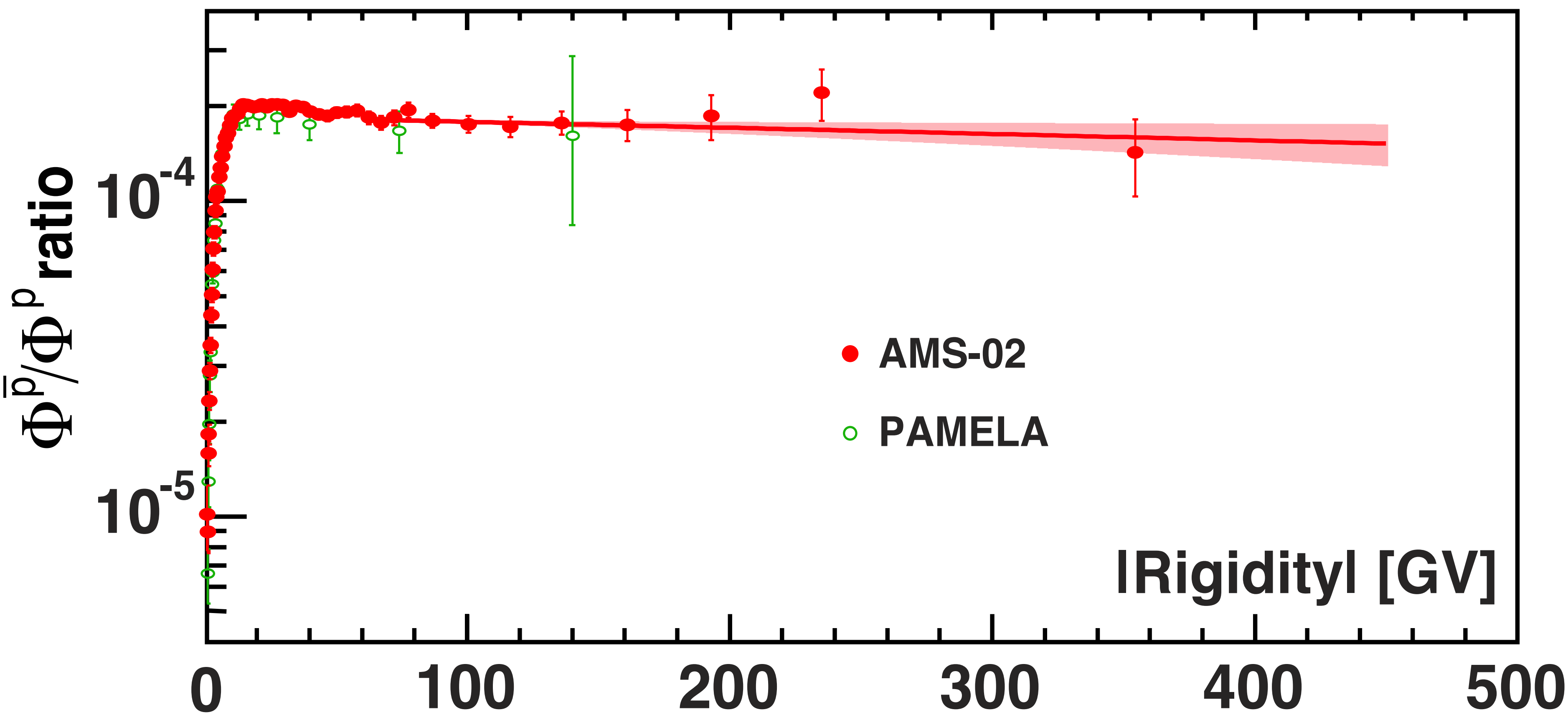
# Anti-protons/proton: 2016

PRL **117**, 091103 (2016) ≈ 350,000 anti-protons

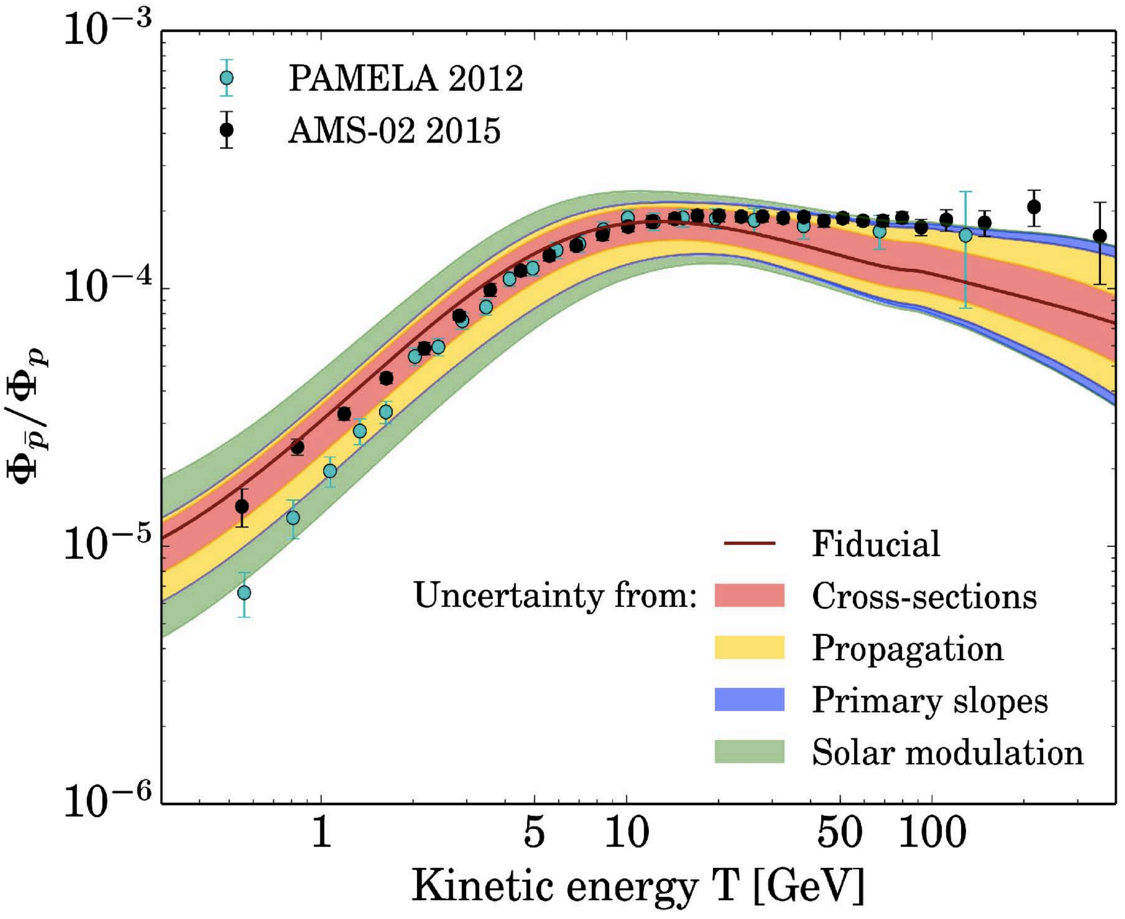


# Anti-protons/proton: 2016

## Energy indipendent above 60 GV



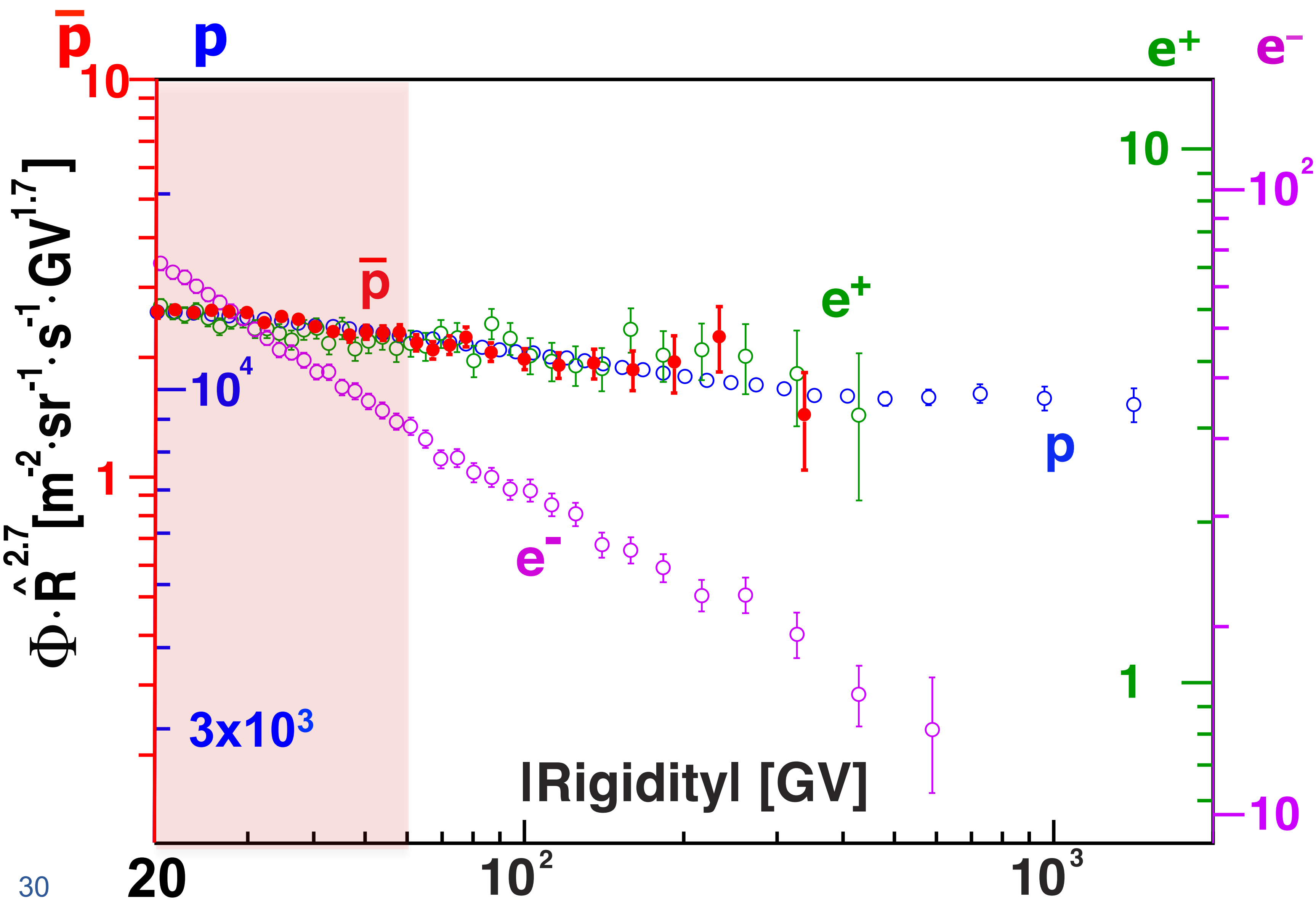
# The accuracy of the latest measurement challenges current knowledge of cosmic background !





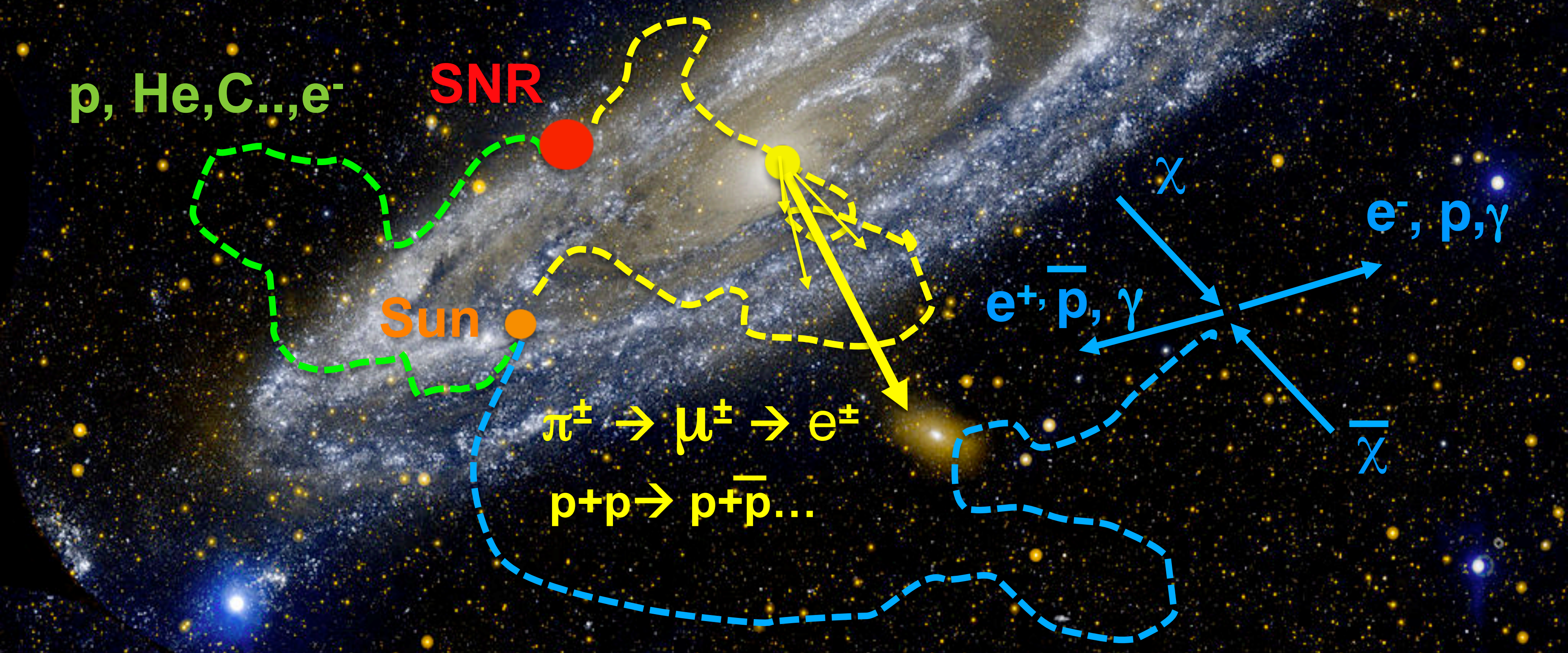

XSCRS 29-31 March @ CERN

# Anti-proton flux : 2016

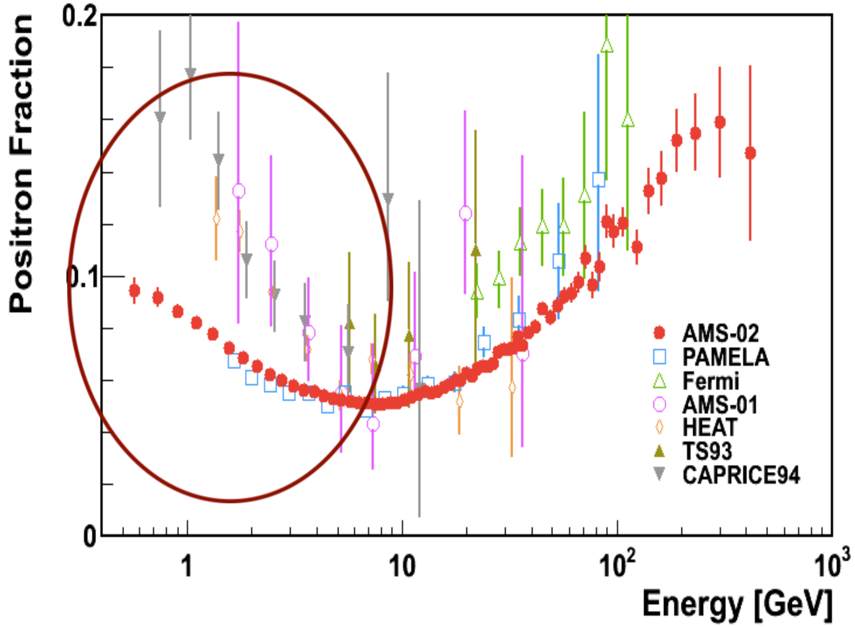


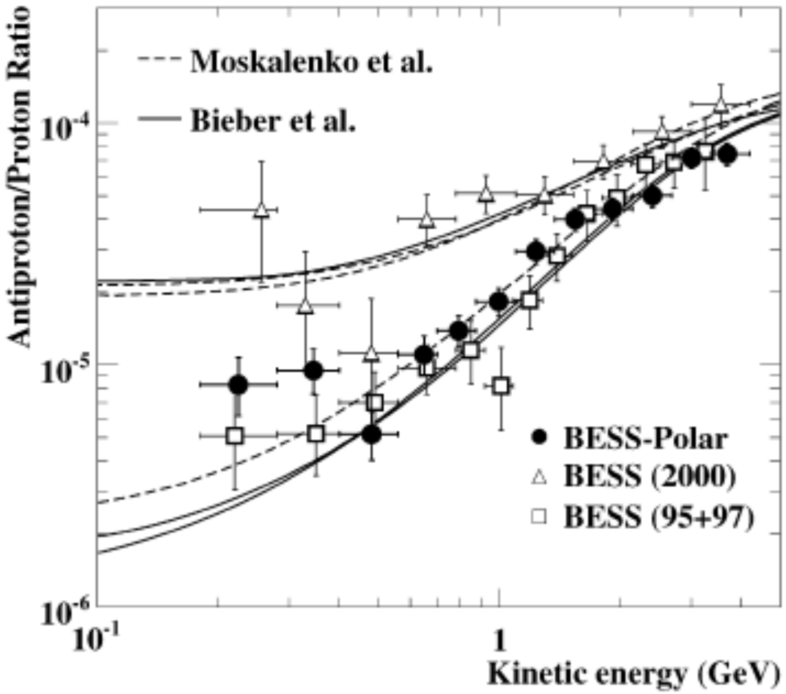
# The DM backgrounds & The CR physics !

- ✓ Origin, acceleration : p, He..
- ✓ propagation & ISM: B/C, Li, Be/B
- ✓ the Sun/Earth effects: time dependence



# Solar effects on CR

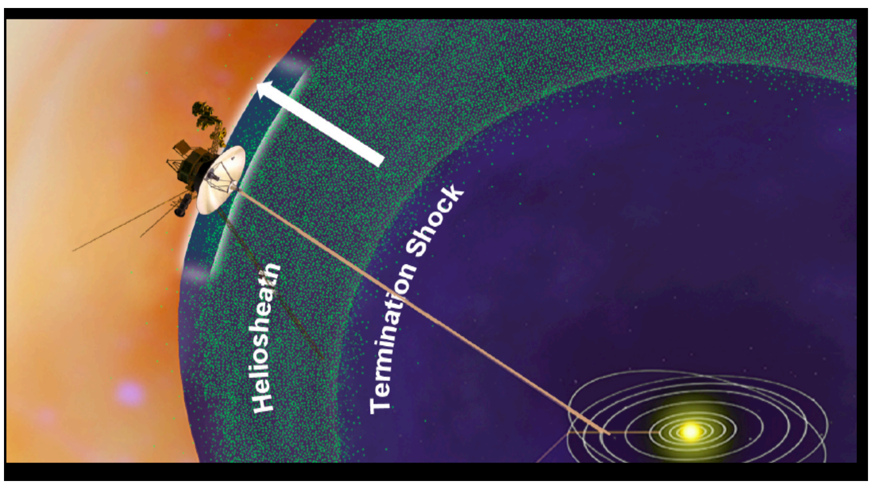


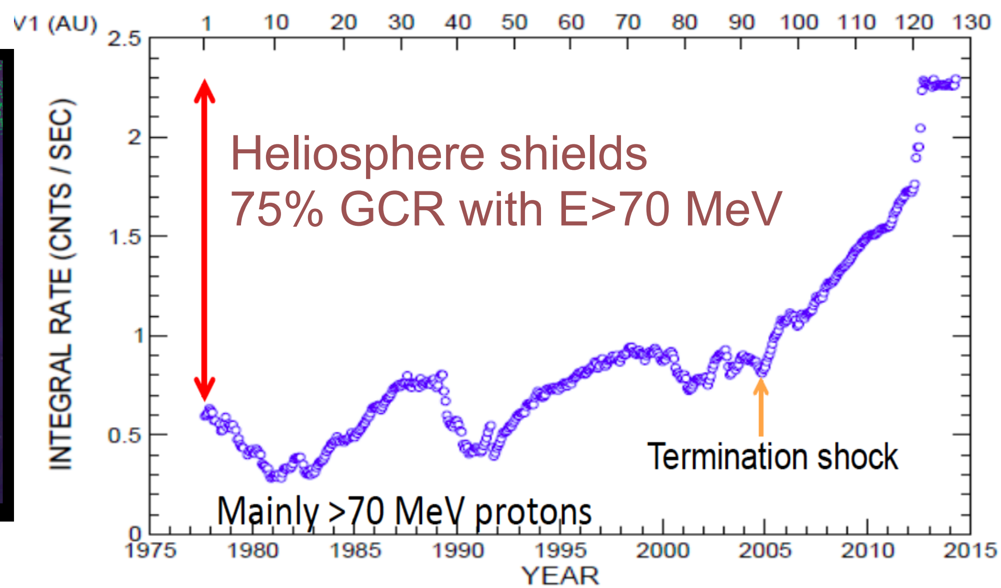



A long journey in planetary mission,
(jupiter, saturn, titan), heliosphere and interstellar space...

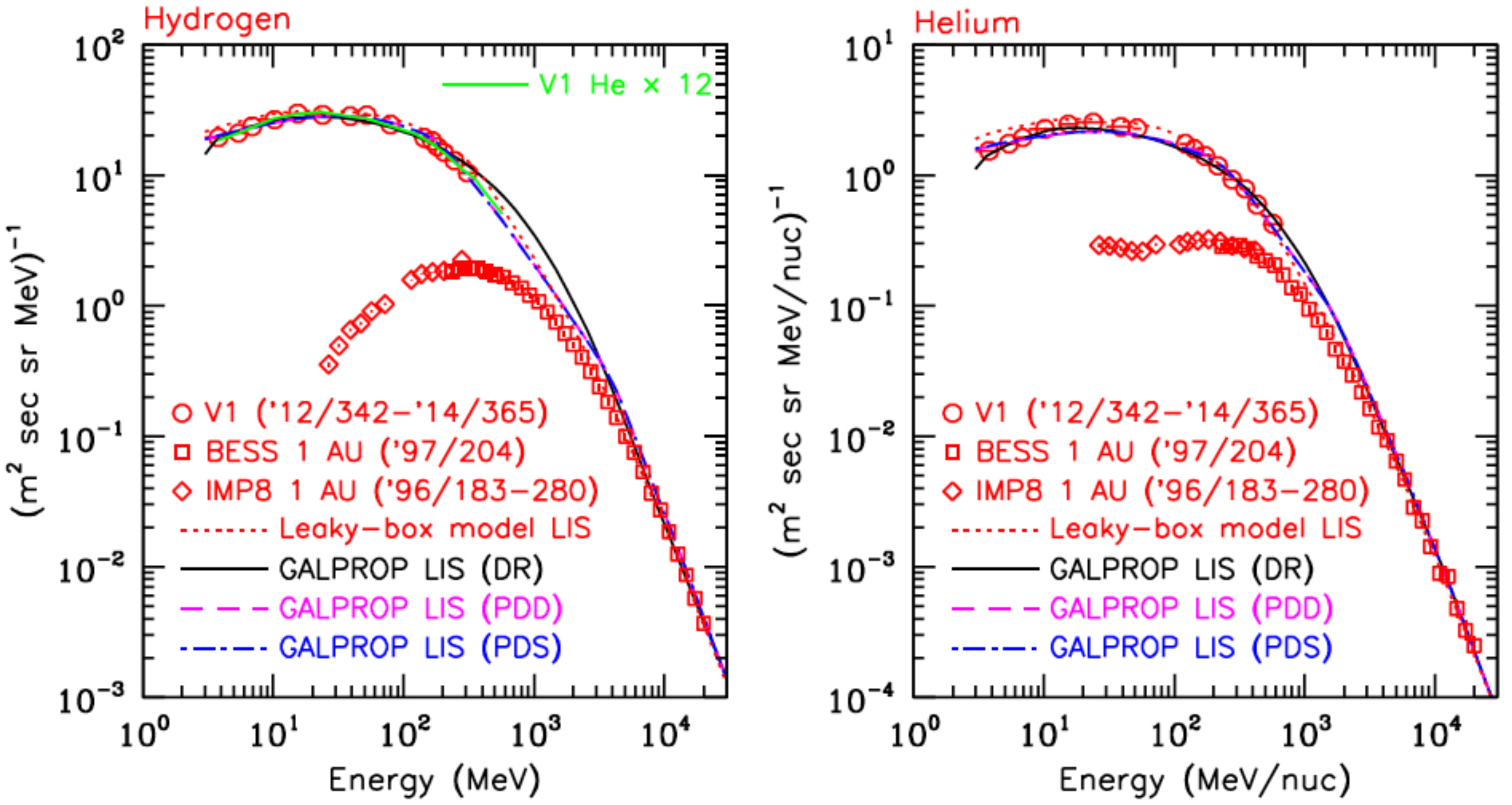
In orbit from Sept.5 1977 :
38 years ..9 months..and still counting (up to 2025...)
@ 121 a.u. out from heliospheric effects !

# Voyager-1
# &
# the (un) modulated CR spectrum

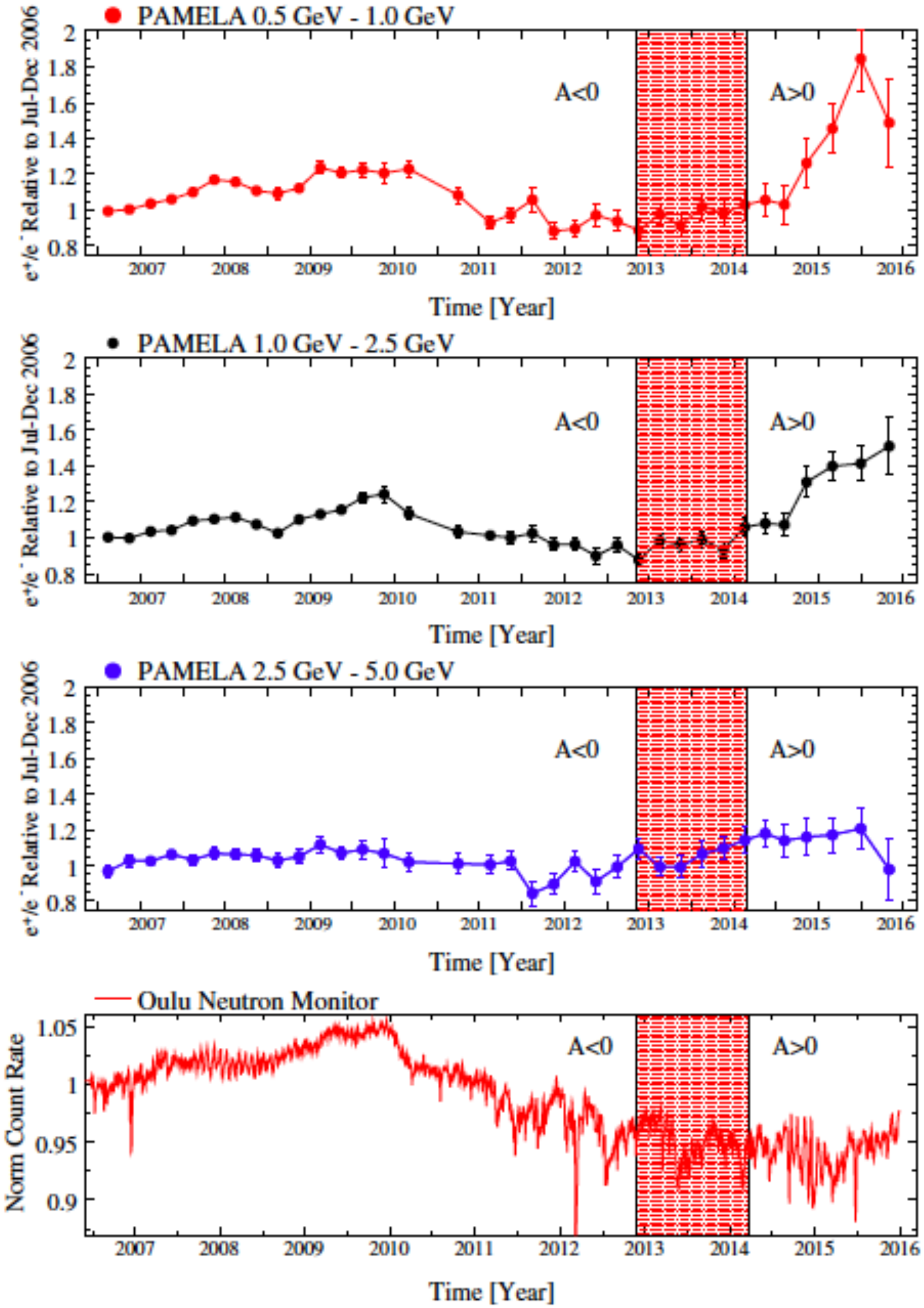


# From the modulated to the unmodulated spectrum...

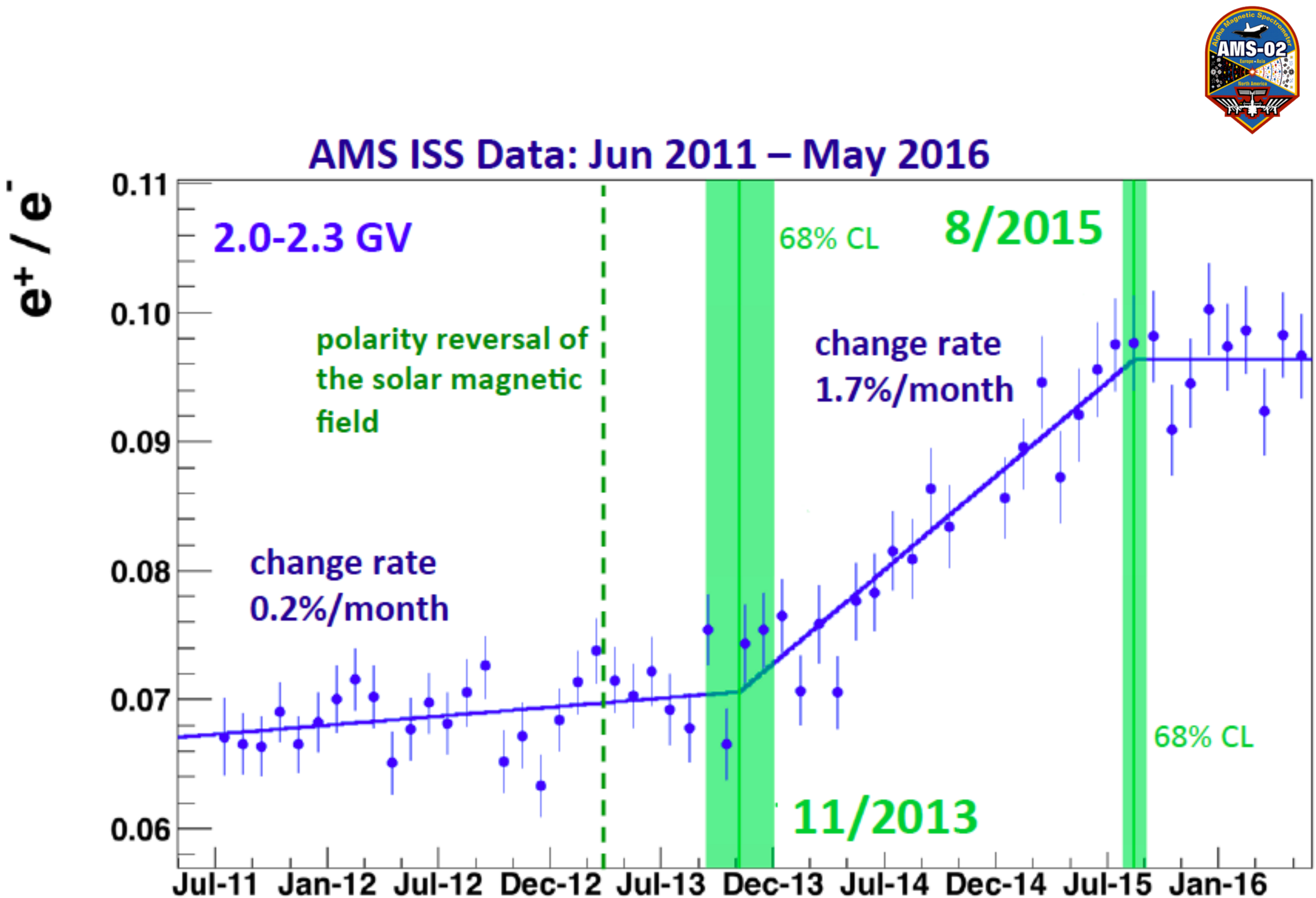



H/He ≈ 12 , flat with energy : shape not due to solar modulation but to ionization losses : V-1 is not near the source !



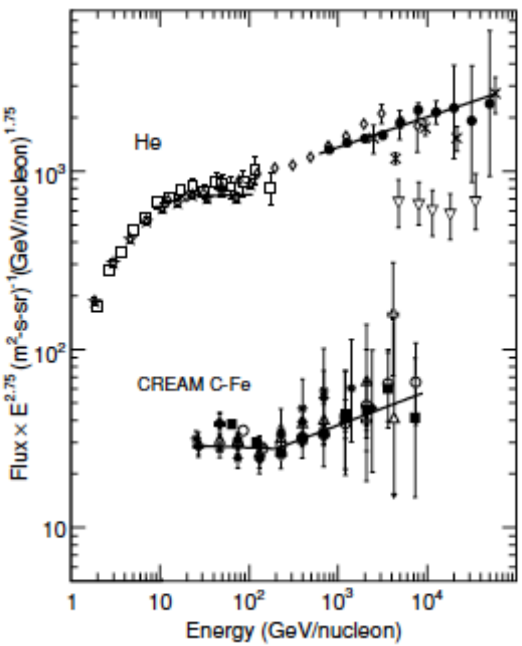

# Time dependance of the electron and positron fluxes

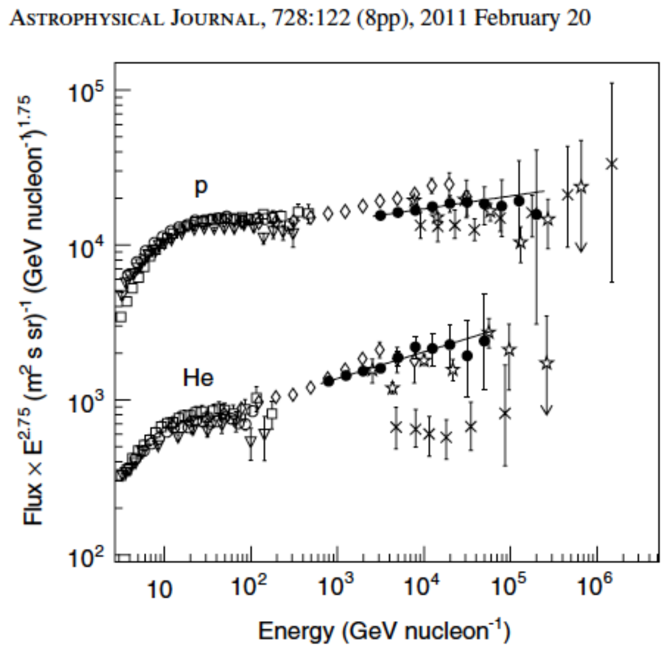
PRL **116**, 241105 (2016)

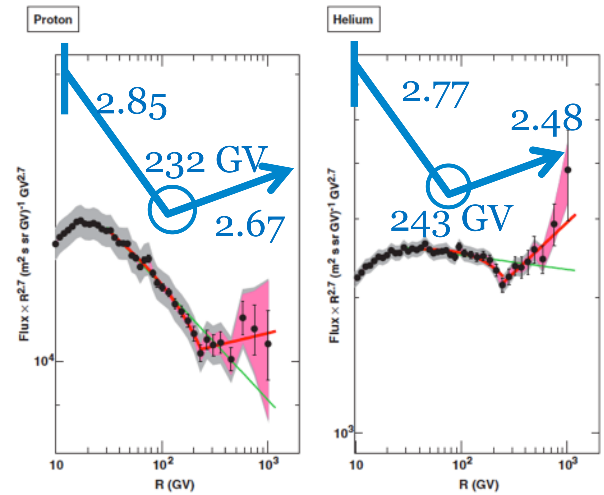

AMS-02
AMS ISS Data: Jun 2011 – May 2016
e+ / e-
2.0-2.3 GV
polarity reversal of
the solar magnetic
field
68% CL
8/2015
change rate
1.7%/month
change rate
0.2%/month
68% CL
11/2013
0.11
0.10
0.09
0.08
0.07
0.06
Jul-11
Jan-12
Jul-12
Dec-12
Jul-13
Dec-13
Jul-14
Dec-14
Jul-15
Jan-16

# Spectral features & composition ....

# Spectral features & composition



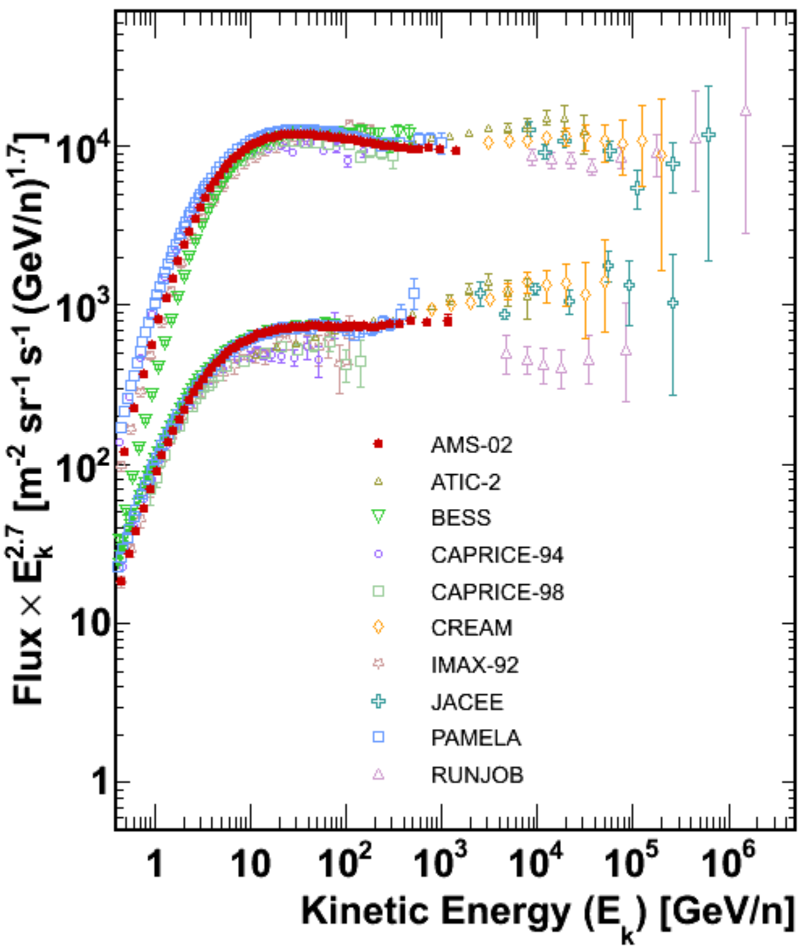



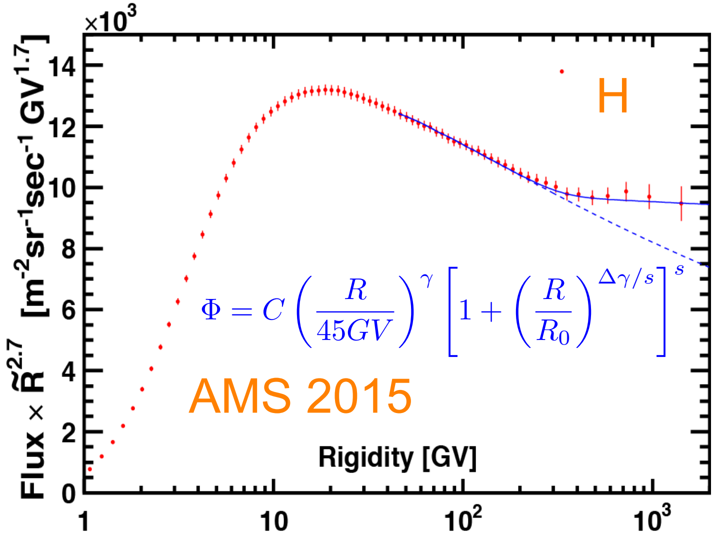

PAMELA, Science 2011

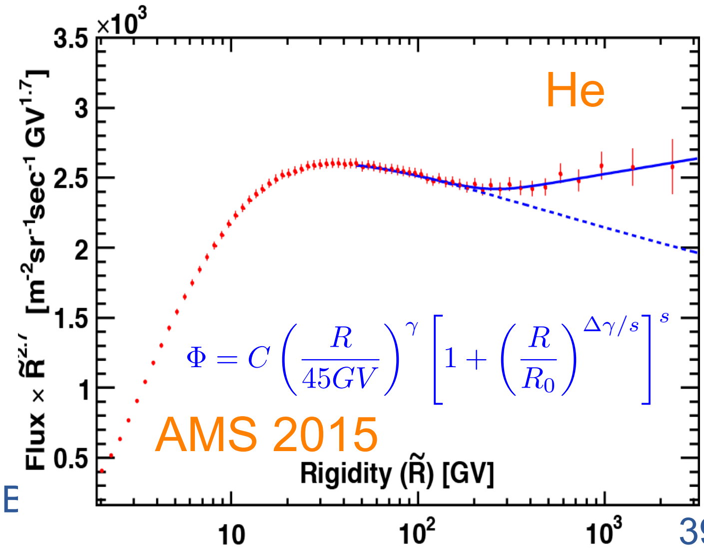
CREAM, APJ 2010, 2011

Breaks occur also at “low” energies…

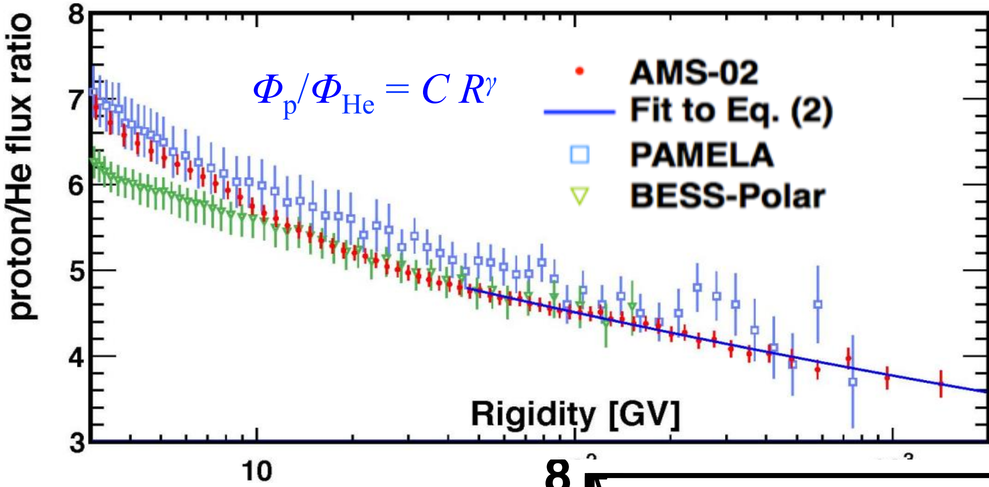
# AMS-02 : the smooth change of spectral index



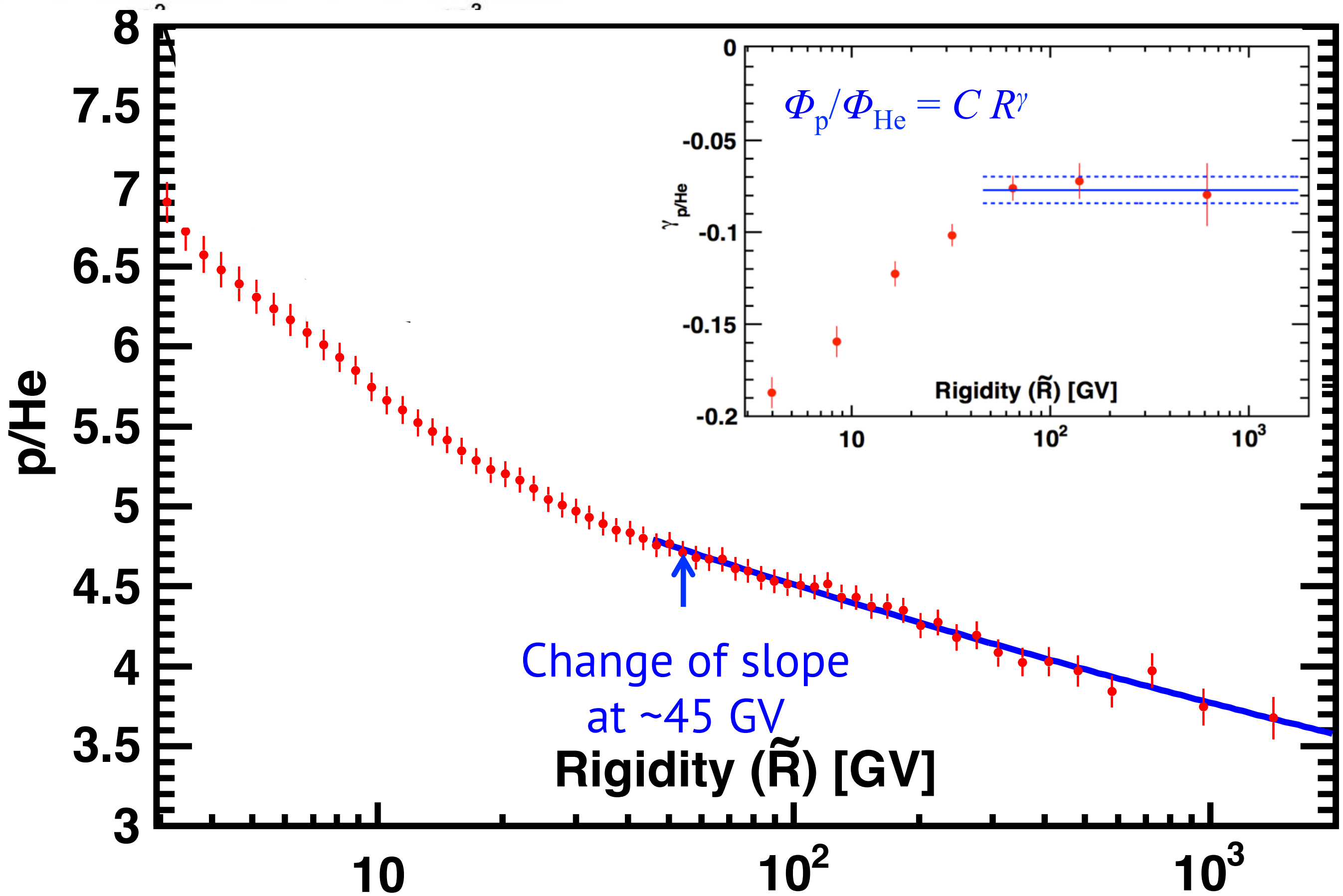




B.E



proton/He flux ratio
$\Phi_p/\Phi_{He} = C\,R^{\gamma}$
AMS-02
Fit to Eq. (2)
PAMELA
BESS-Polar
Rigidity [GV]

p/He
$\Phi_p/\Phi_{He} = C\,R^{\gamma}$
$\gamma_{p/He}$
Rigidity (R̃) [GV]
Change of slope
at ~45 GV
Rigidity (R̃) [GV]

# What about origin of spectral hardening?

Related to acceleration mechanisms at source?

- distributed acceleration by multiple sources at the origin ?
- non linear DSA?
- reacceleration by weak shocks in the Galaxy?

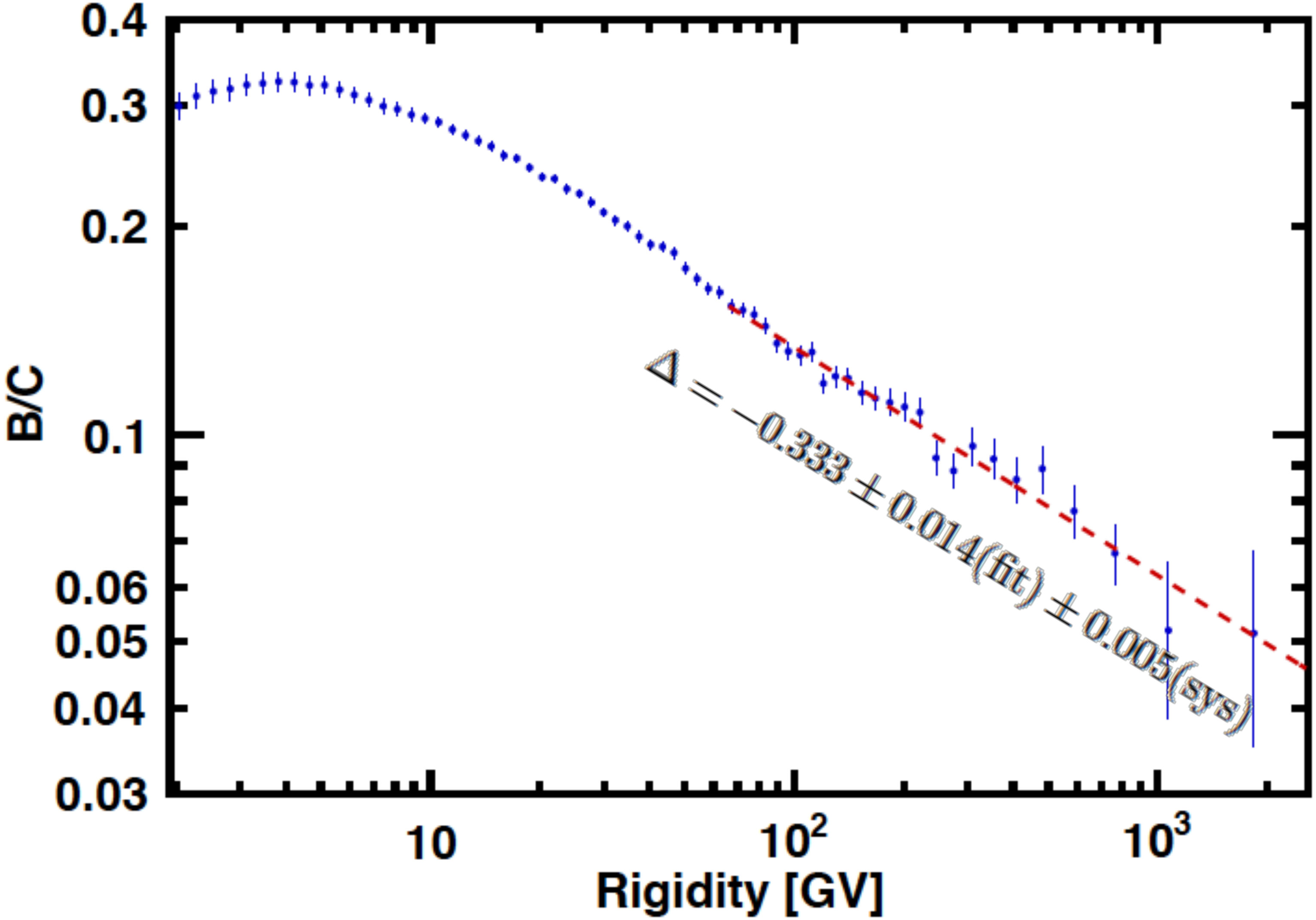
Propagations effects?
e.g. space and energy dependent diffusion coefficients?

Effect of nearby young CR sources?

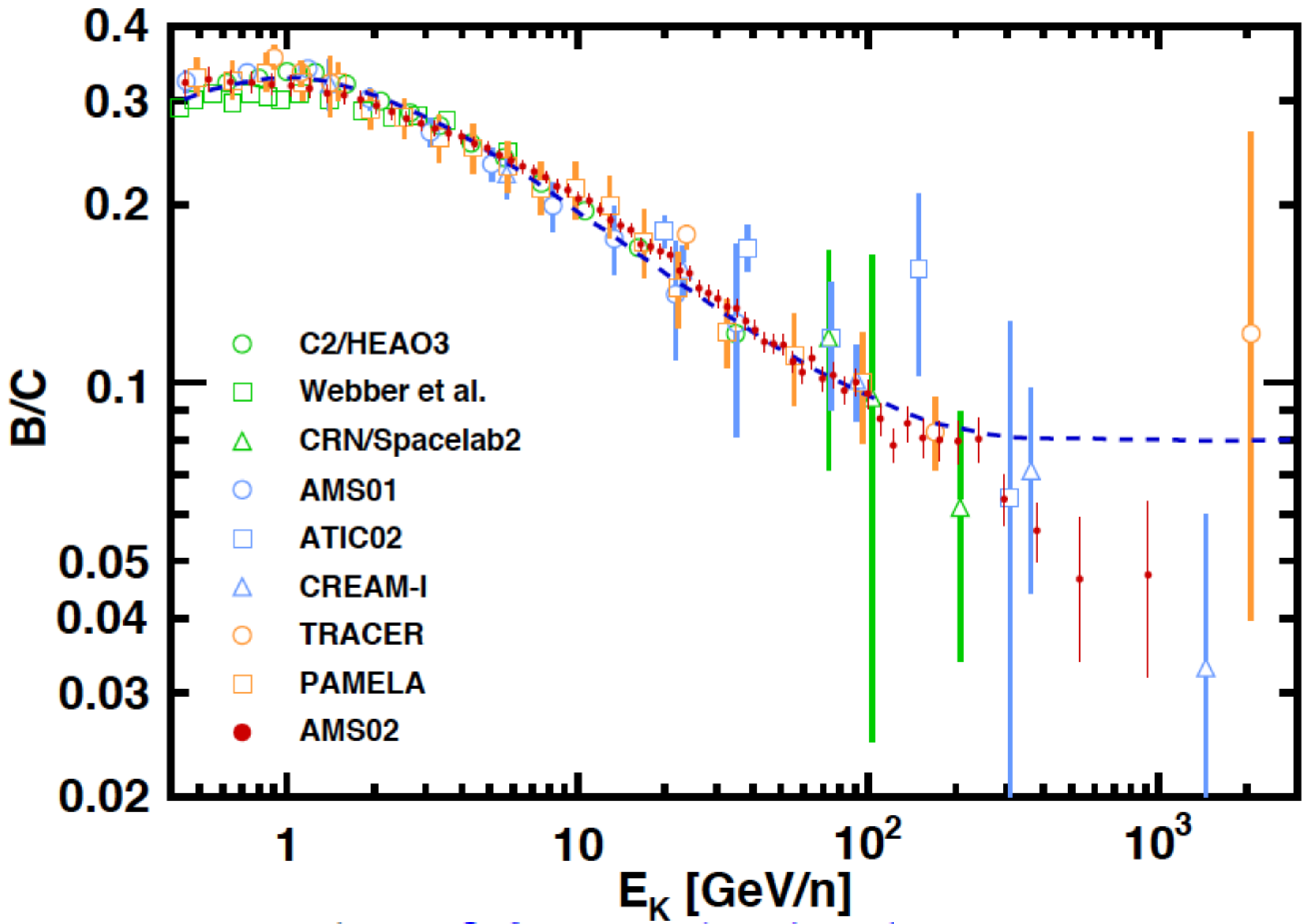
**Future promises more & more fun:**
precise data also on other primary/secondary species are coming;

- AMS released just a small part of his data...and will continue to run as the ISS will be operational
- DAMPE
- CALET
- ISS-CREAM
- (HERD, ALADINO?)

# B/C ratio 2016 (sub. PRL)

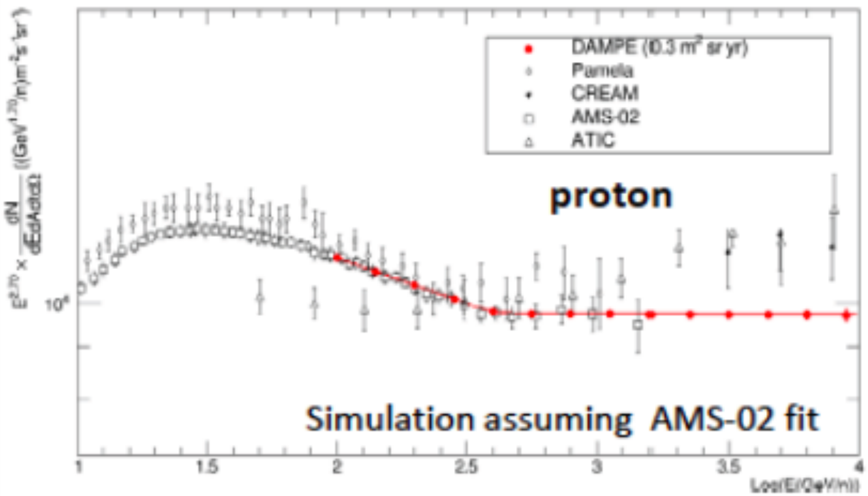


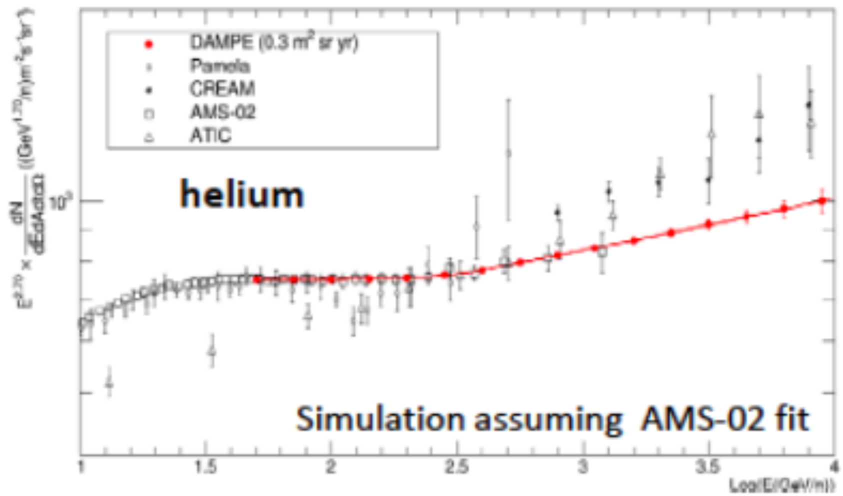
# B/C ratio 2016 (AMS sub. PRL)



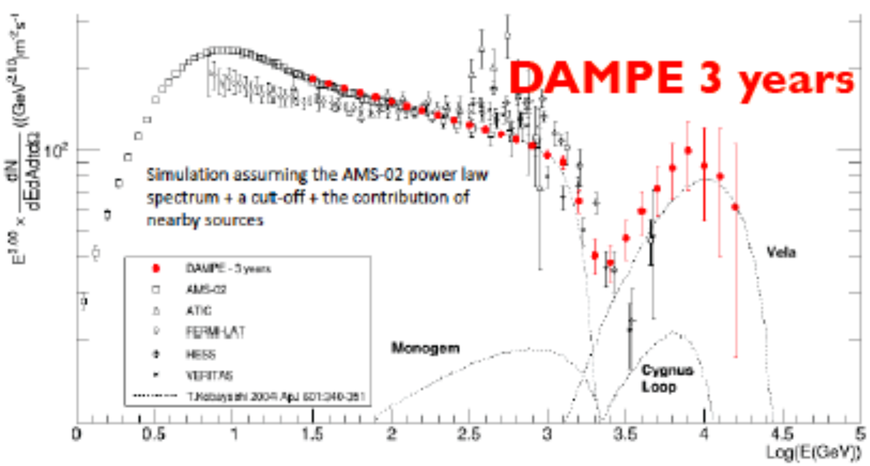

Model R. Cowsik Astrophys. J. 786, 124 (2014)

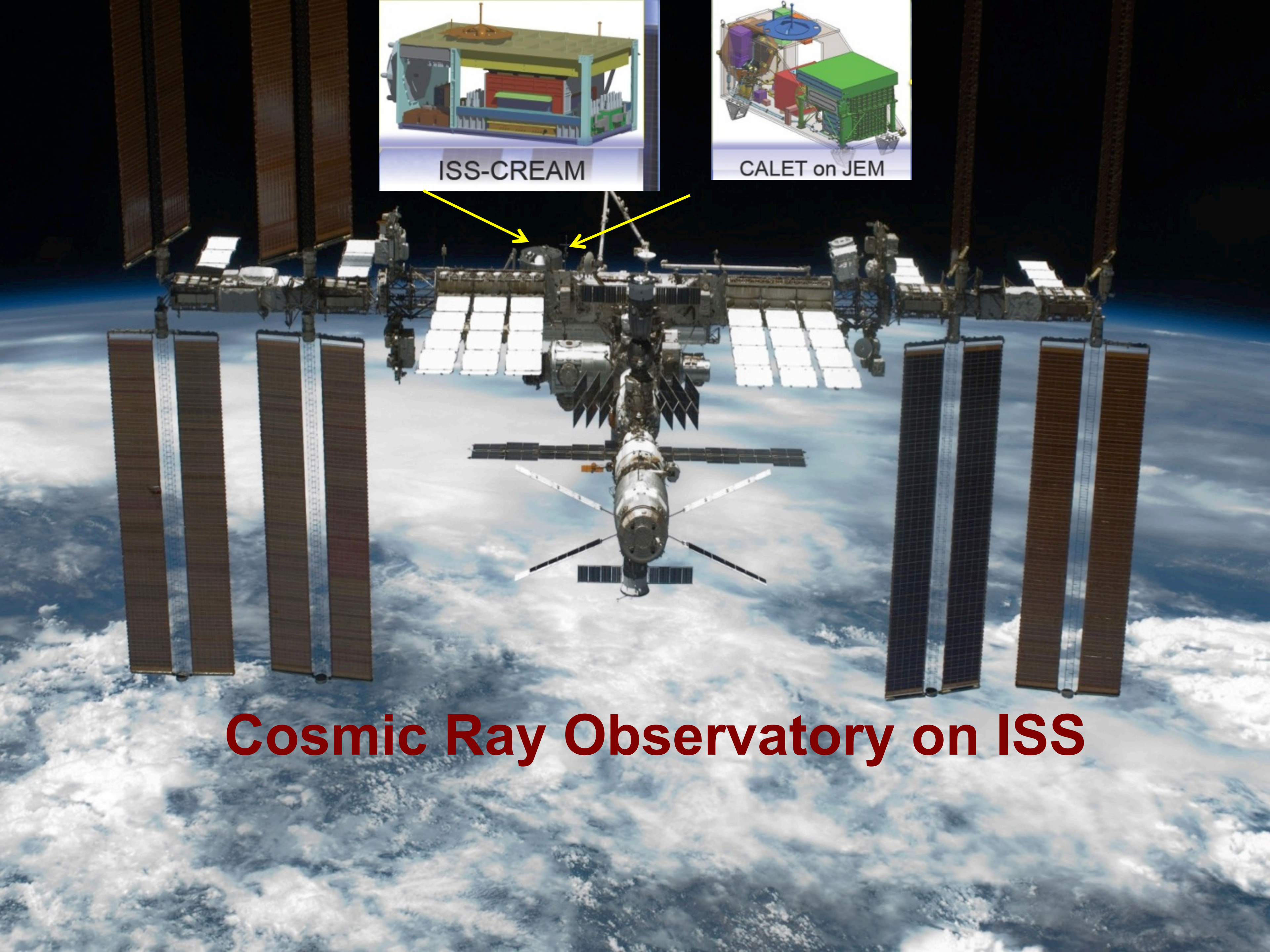
# Expected measurements



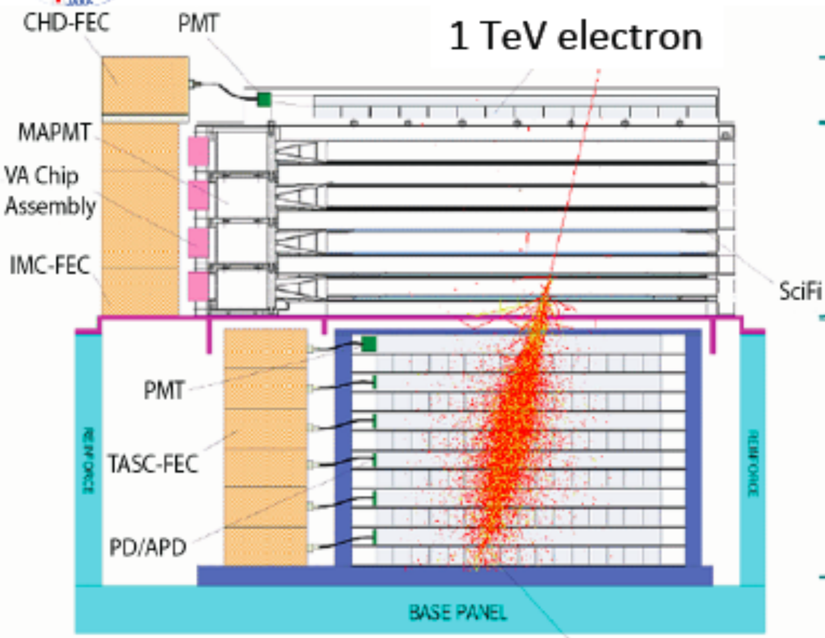




- ➢ Proton and nuclei up to 100Tev
- ➢ Electron Spectrum up to 10 TeV
  - ✓ Detect the possible cutoff around 1TeV
  - ✓ Detect possible spectrum structures and anisotropies (DM signals)




ISS-CREAM
CALET on JEM
Cosmic Ray Observatory on ISS

# CALorimetric Electron Telescope (CALET): INSTRUMENT OVERVIEW




CHD - **CHarge Detector (CHD)**
(Charge Measurement Z=1-40)

IMC - **Imaging Calorimeter (IMC)**
(Particle ID, Direction)

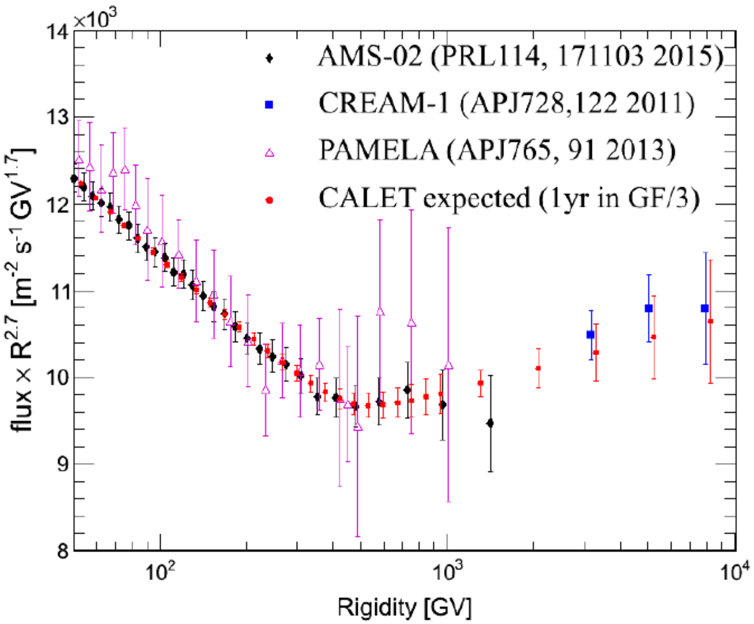
Total Thickness of Tungsten (W): $3\ X_0$, $0.1\ \lambda_I$
Layer Number of Scifi Belts: 8 Layers × 2(X,Y)

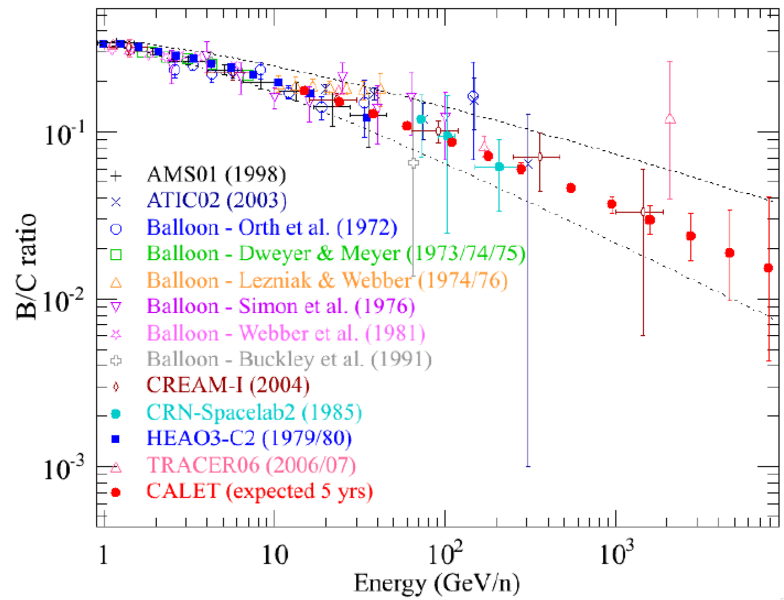
TASC - **Total Absorption Calorimeter (TASC)**
(Energy Measurement, Particle ID)

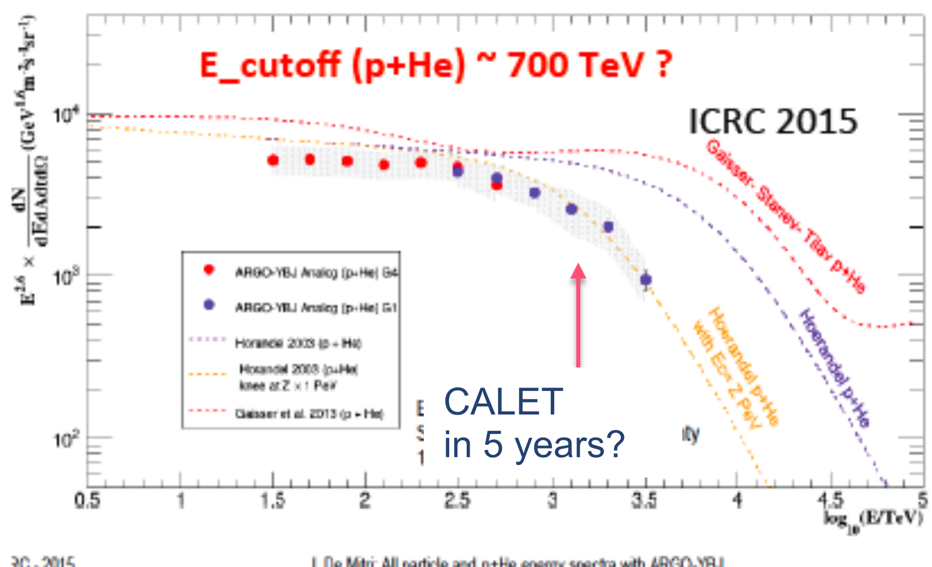
PWO 20mm x 20mm x 320mm
Total Depth of PWO: $27\ X_0$ (24 cm), $1.2\ \lambda_I$

| | CHD (Charge Detector) | IMC (Imaging Calorimeter) | TASC (Total Absorption Calorimeter) |
|---|---|---|---|
| Function | Charge Measurement (Z = 1 - 40) | Arrival Direction, Particle ID | Energy Measurement, PID |
| Sensor (+ Absorber) | Plastic Scintillators: 2 layers<br>Unit Size: 32mm x 10mm x 450mm | Scintillating Fibers: 16 layers<br>single readout: $1mm^2$ x 448 mm<br>Total thickness of Tungsten: $3\ X_0$ | PWO logs: 12 layers<br>Unit size: 19mm x 20mm x 326mm<br>Total Thickness of PWO: $27\ X_0$ |
| Readout | PMT+CSA | 64-anode MAPMT+ ASIC | APD/PD+CSA<br>PMT+CSA ( for Trigger) |

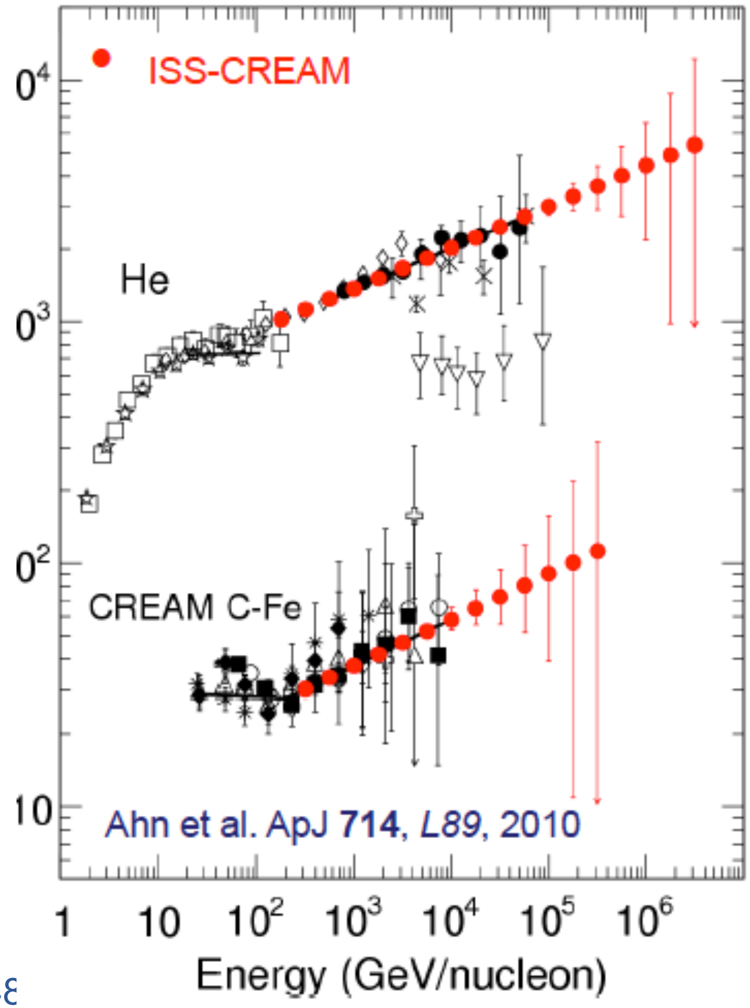
# CALET & CR ...

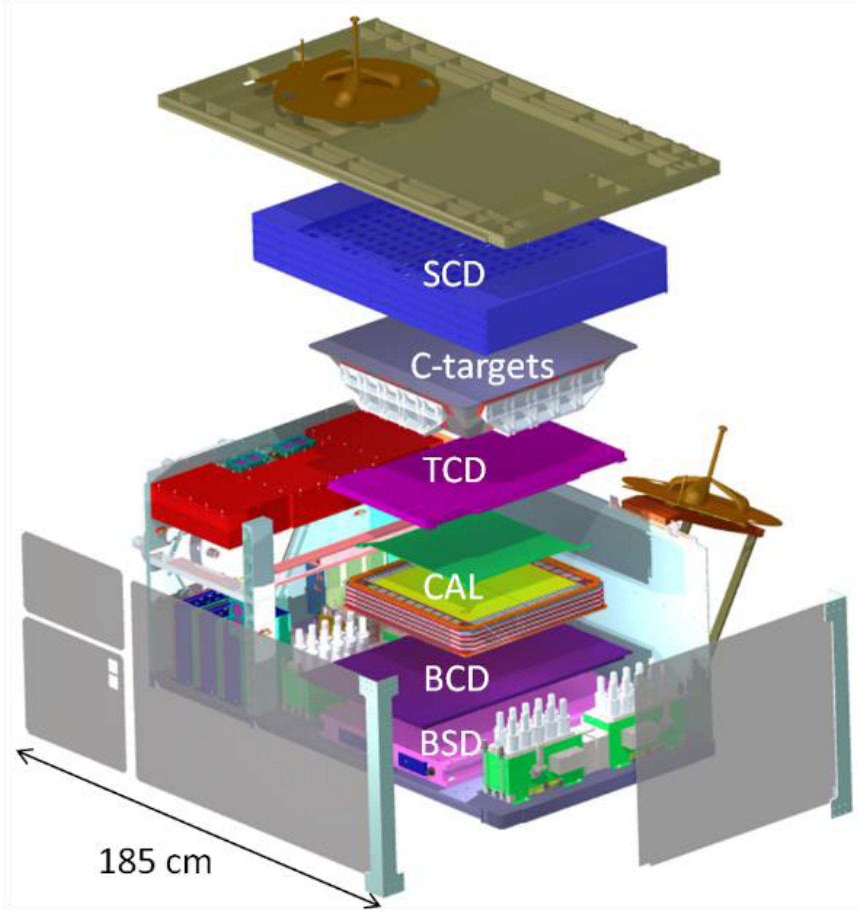

×10³
AMS-02 (PRL114, 171103 2015)
CREAM-1 (APJ728,122 2011)
PAMELA (APJ765, 91 2013)
CALET expected (1yr in GF/3)
flux × R^2.7 [m^-2 s^-1 GV^1.7]
Rigidity [GV]


AMS01 (1998)
ATIC02 (2003)
Balloon - Orth et al. (1972)
Balloon - Dweyer & Meyer (1973/74/75)
Balloon - Lezniak & Webber (1974/76)
Balloon - Simon et al. (1976)
Balloon - Webber et al. (1981)
Balloon - Buckley et al. (1991)
CREAM-I (2004)
CRN-Spacelab2 (1985)
HEAO3-C2 (1979/80)
TRACER06 (2006/07)
CALET (expected 5 yrs)
B/C ratio
Energy (GeV/n)


E_cutoff (p+He) ~ 700 TeV ?
ICRC 2015
Gaisser-Stanev-Tilav p+He
Hoerandel p+He
Hoerandel p+He with Ec= Z PeV
CALET
in 5 years?
log10(E/TeV)
I. De Mitri: All particle and p+He energy spectra with ARGO-YBJ

# ISS-CREAM : launch June 1st 2017



# Conclusions & Perspectives

- ✓ Stratospheric balloon program is still relevant for specific measurements (GAPS for anti-d ?..)
- ✓ Space is giving an important contribution to direct CR measurements…
  - ✓ PAMELA did a great job…
  - ✓ AMS-02 is starting to release impressive results..and more will come in the next future
  - ✓ CALET and DAMPE just launched...

- ✓ in 10 years large acceptance space based calorimetric experiments insuring good overlap with ground based (indirect) measurements (HERD?)

- ✓ Anti-matters matters ! A long term plan is needed (and is starting..) for a new antimatter large acceptance detector in orbit ..

# China's Space Station Program

2022

Phase -II

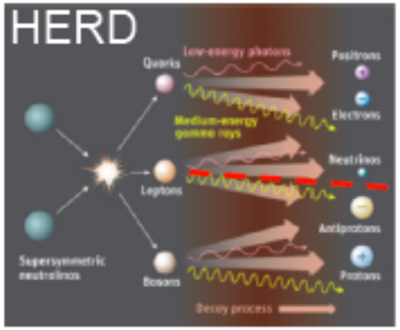
2018

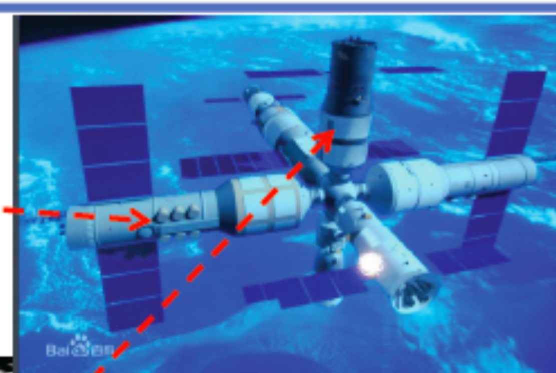
Phase -II

2011

Phase -I

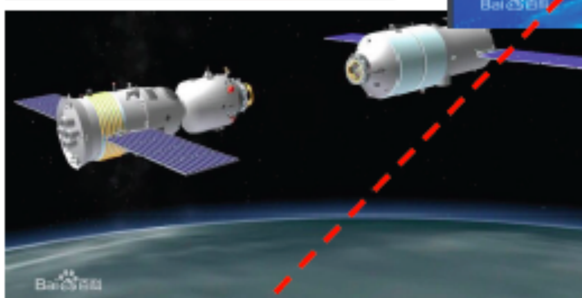
2003



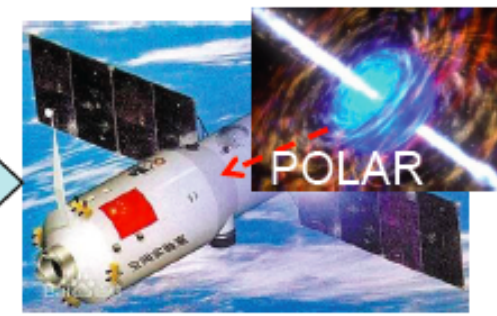



**Space Station**

3 large modules
+ 2 m telescope
~10-year lifetime



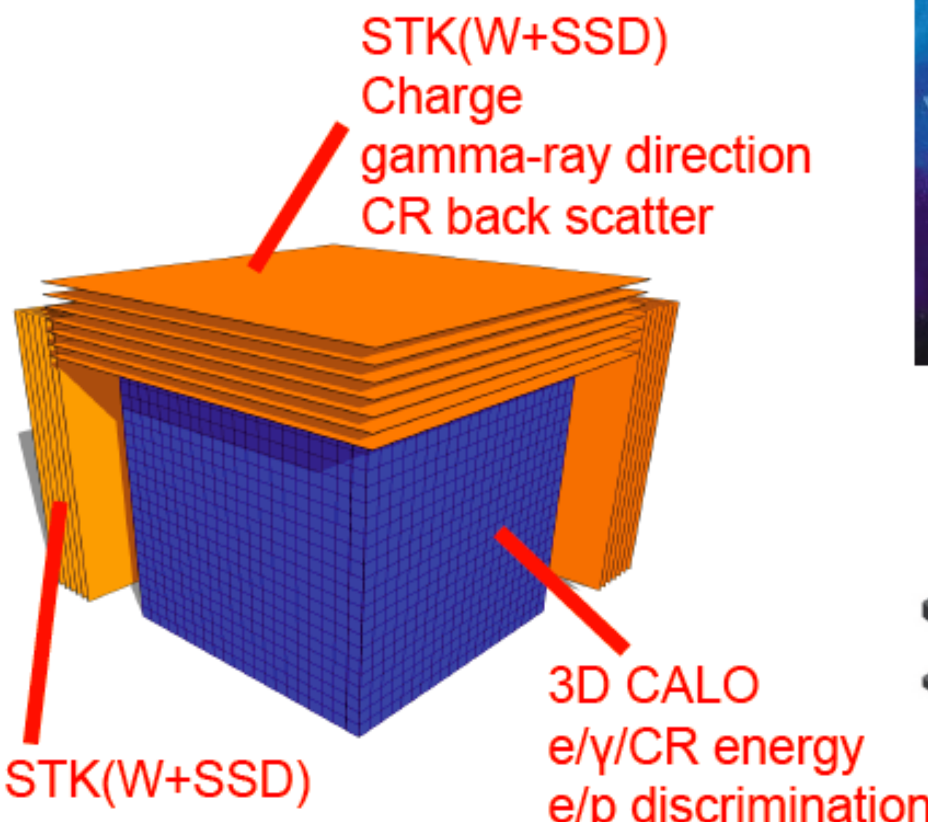
**Space lab:**
no living cabin

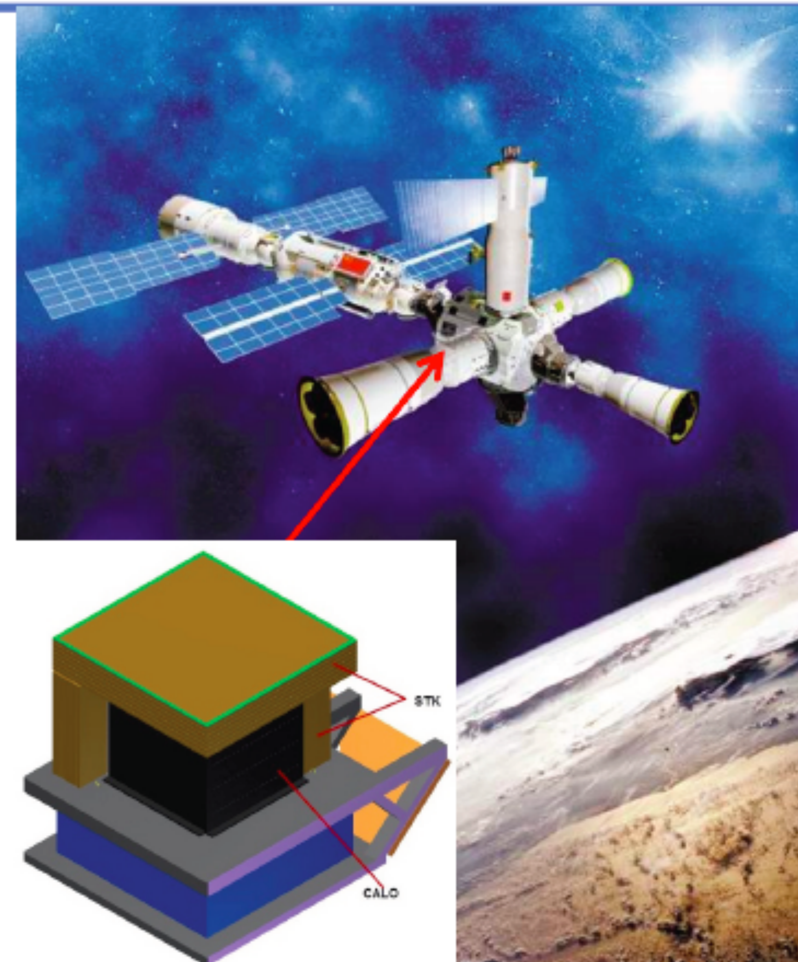



10 astronauts in 5 flights → space walk

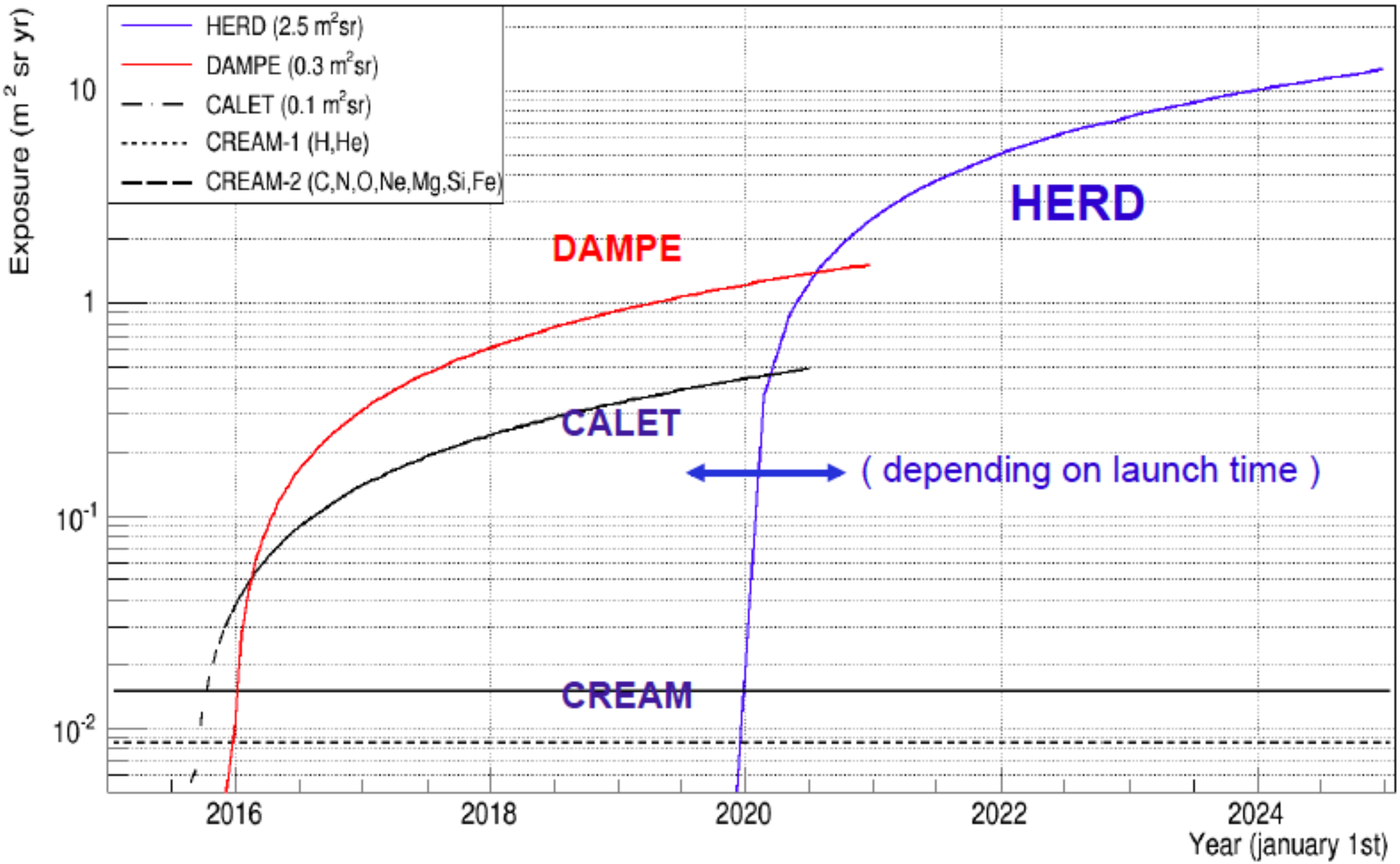
# High Energy cosmic-Ray Detector (HERD)

n10X acceptance than others, but weight 2.3 T ~1/3 AMS

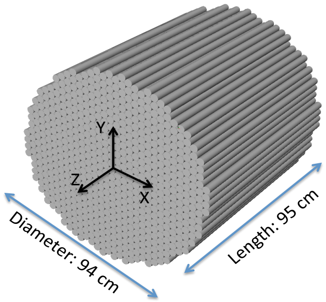


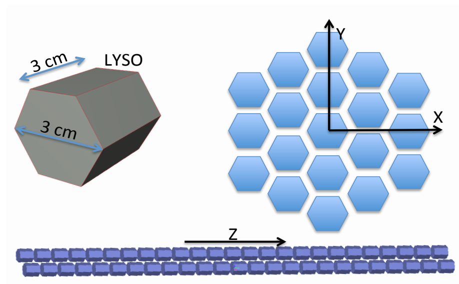



# Exposure (assuming GF=2.5m²sr)



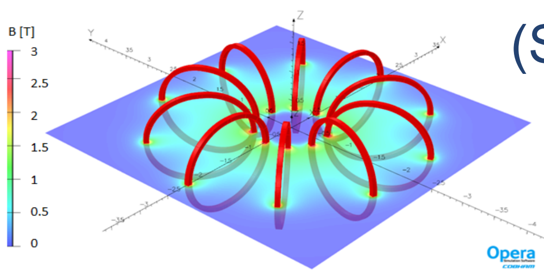
# Antimatter Large Acceptance Detector IN Orbit (ALADINO)



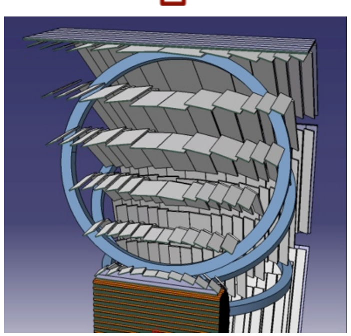




3D calorimetry
(CaloCube)

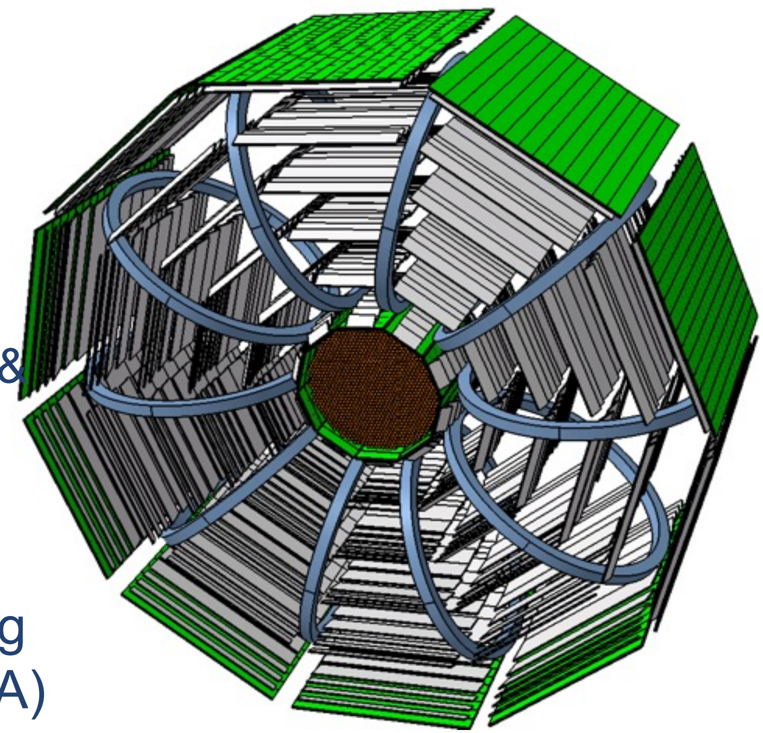
HTC SC
(SR2S)




Average B ≈ 0.8&



Silicon Tracking
(AMS, PAMELA)



# Aladino

| | |
|---|---|
| Calorimeter acceptance | ~ 9 $m^2$ sr |
| Spectrometer acceptance | ~ 3 $m^2$ sr |
| Spectrometer Maximum Detectable Rigidity | > 20 TV |
| Calorimeter energy resolution | 24% ÷ 35% (for nuclei)<br>2% (for electrons and positrons) |
| Calorimeter e/p rejection power | > $10^5$ |
| Time of Flight measurement resolution | 180 ps |

**Table 1:** *main performance parameters of the ALADINO apparatus*